Boosting Higgs Discovery

Graham Kribs

Fermilab & U Oregon

Wine & Cheese 4 Feb 2011


R

Ben Lee

1935–1977

- First paper with "Higgs phenomena" in title (1971)
- Upper bound on Higgs mass from unitarity "Lee-Quigg-Thacker bound"
- Classic "Lee-Weinberg" bound on neutral lepton masses
- Series on renormalizabilty of gauge theories

"I, personally, know of no one who claimed to understand the details of 't Hooft's paper. Rather we all learned it from Ben Lee, who combined insights from his own work"

Politzer Nobel Lecture

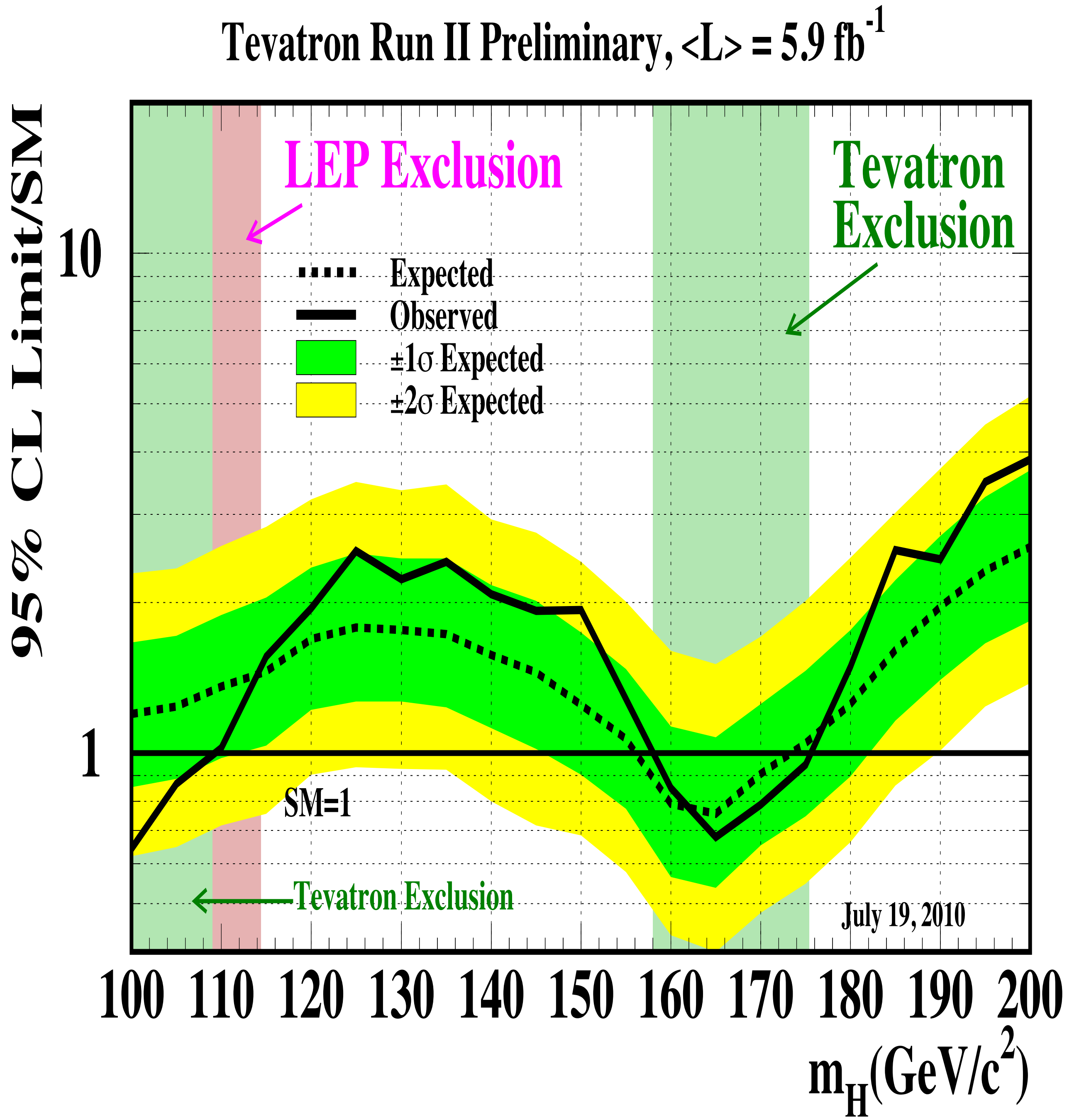
Outline

- Higgs in Standard Model
- Jet Substructure applied to $h \to b\bar{b}$ @ LHC
- Higgs in new physics:
  i) SUSY
  ii) top-partners
- Discovery of Higgs in new physics events
- Summary

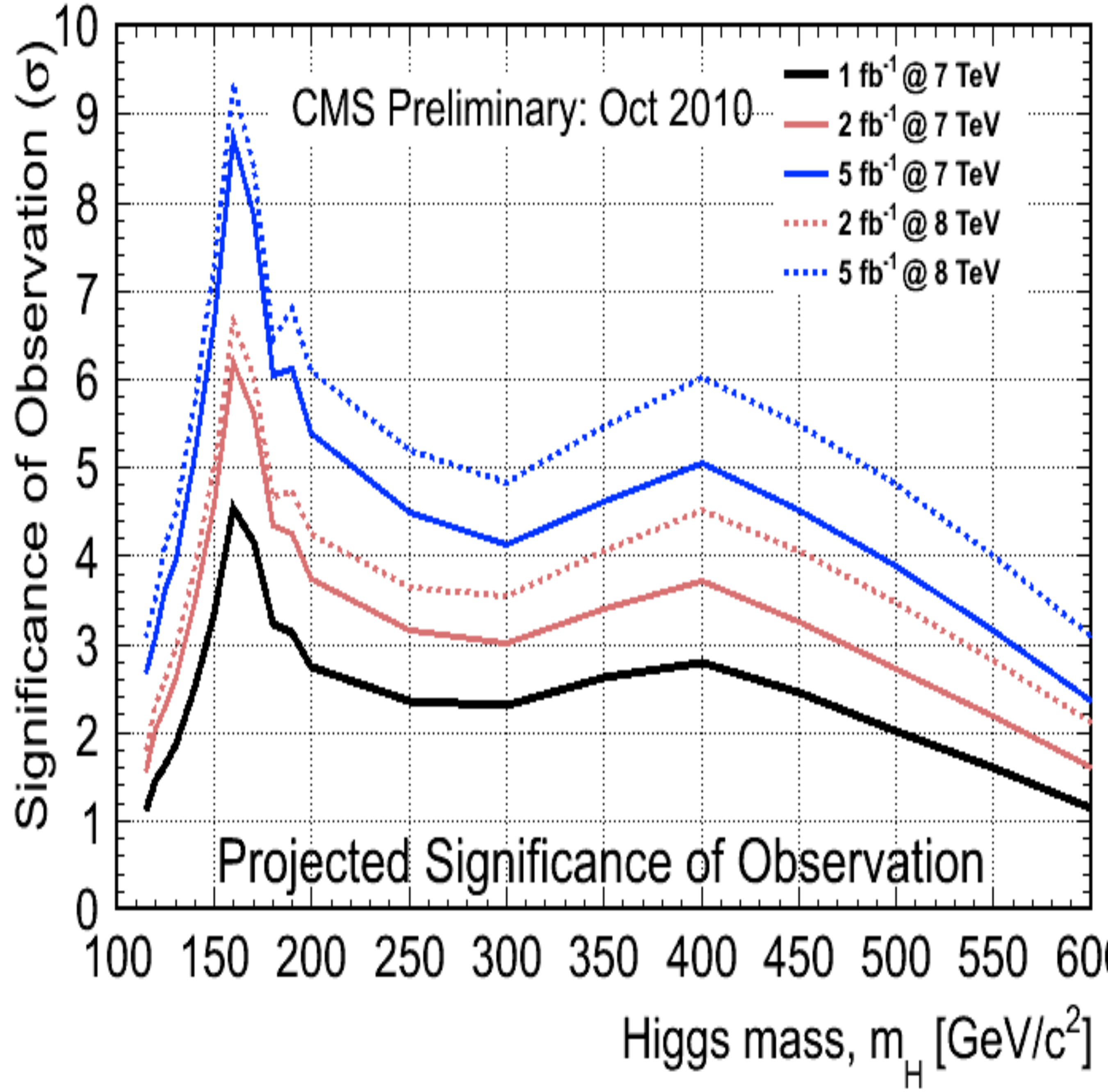
Outline

- Higgs in Standard Model
- Jet Substructure applied to h -> $b\bar{b}$ @ LHC
- Higgs in new physics:
  i) SUSY
  ii) top-partners
- Discovery of Higgs in new physics events
- Summary

Era of Higgs Physics

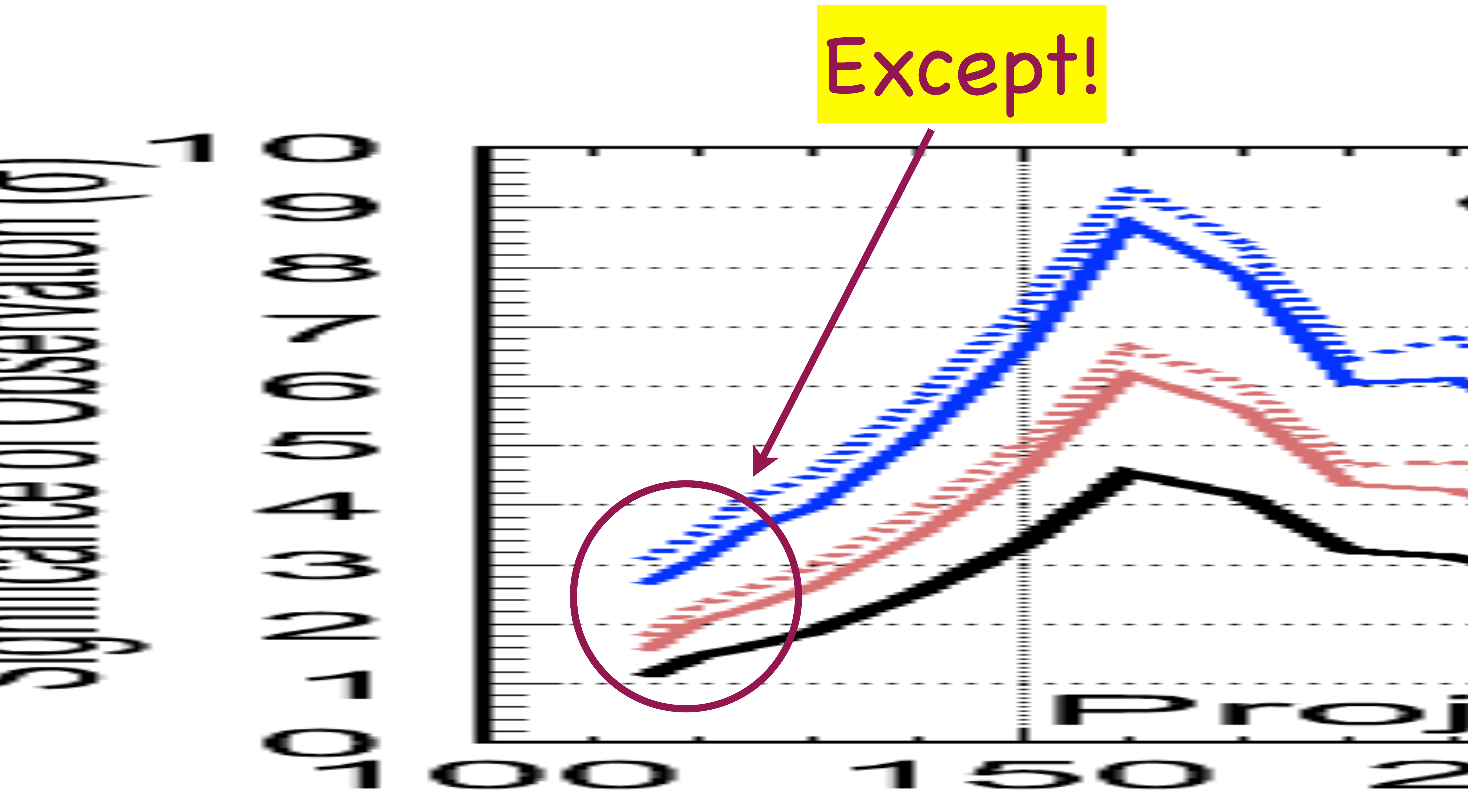


1007.4587

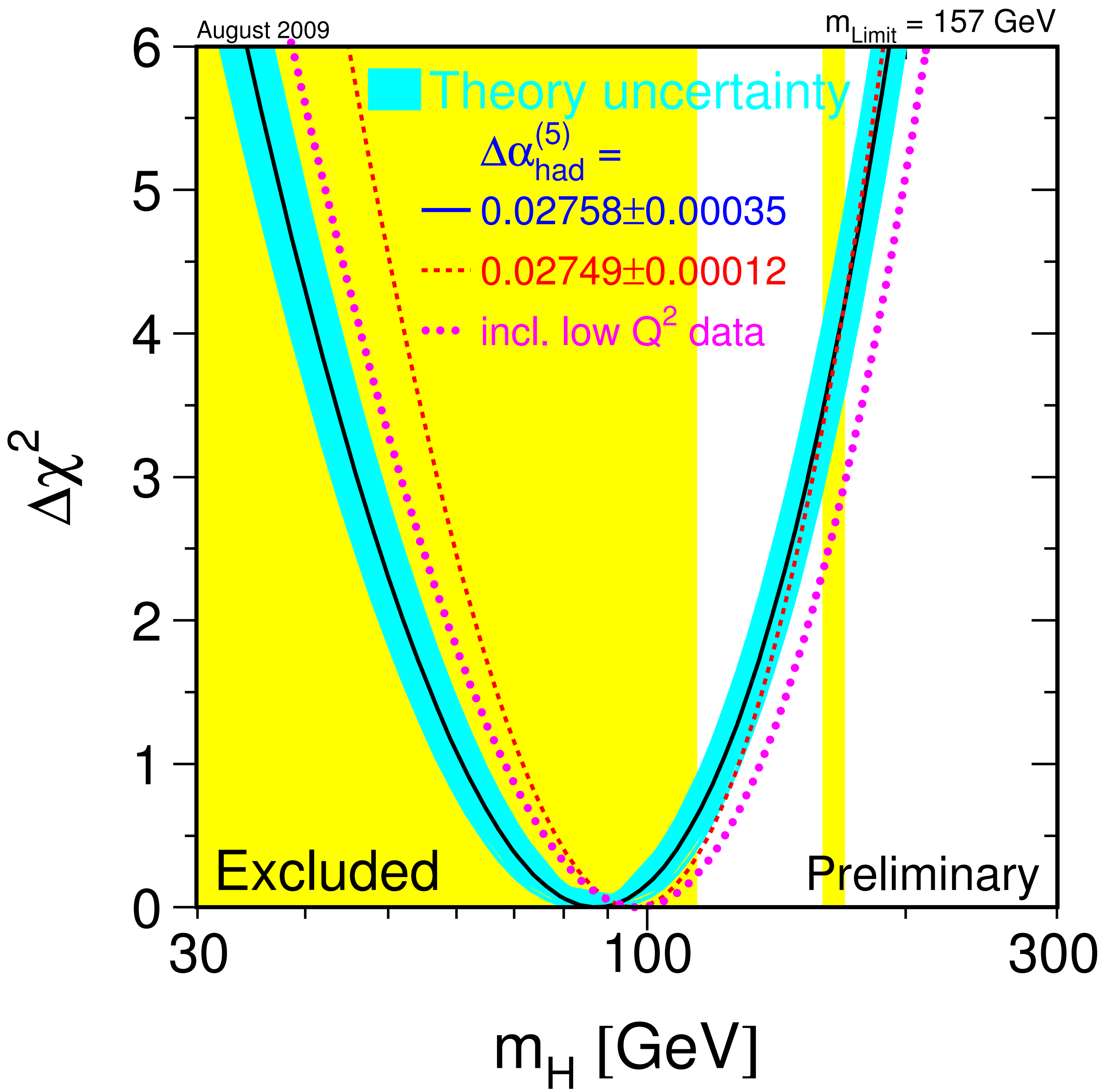


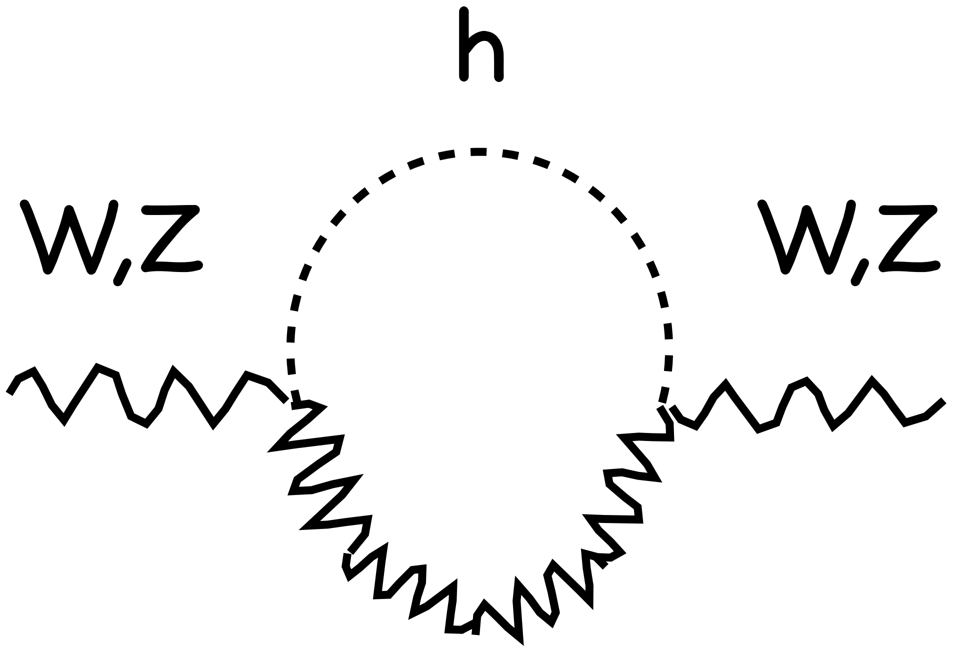
updated CMS NOTE-2010/008

"Almost" discovery (or rule out) within 1-2 years

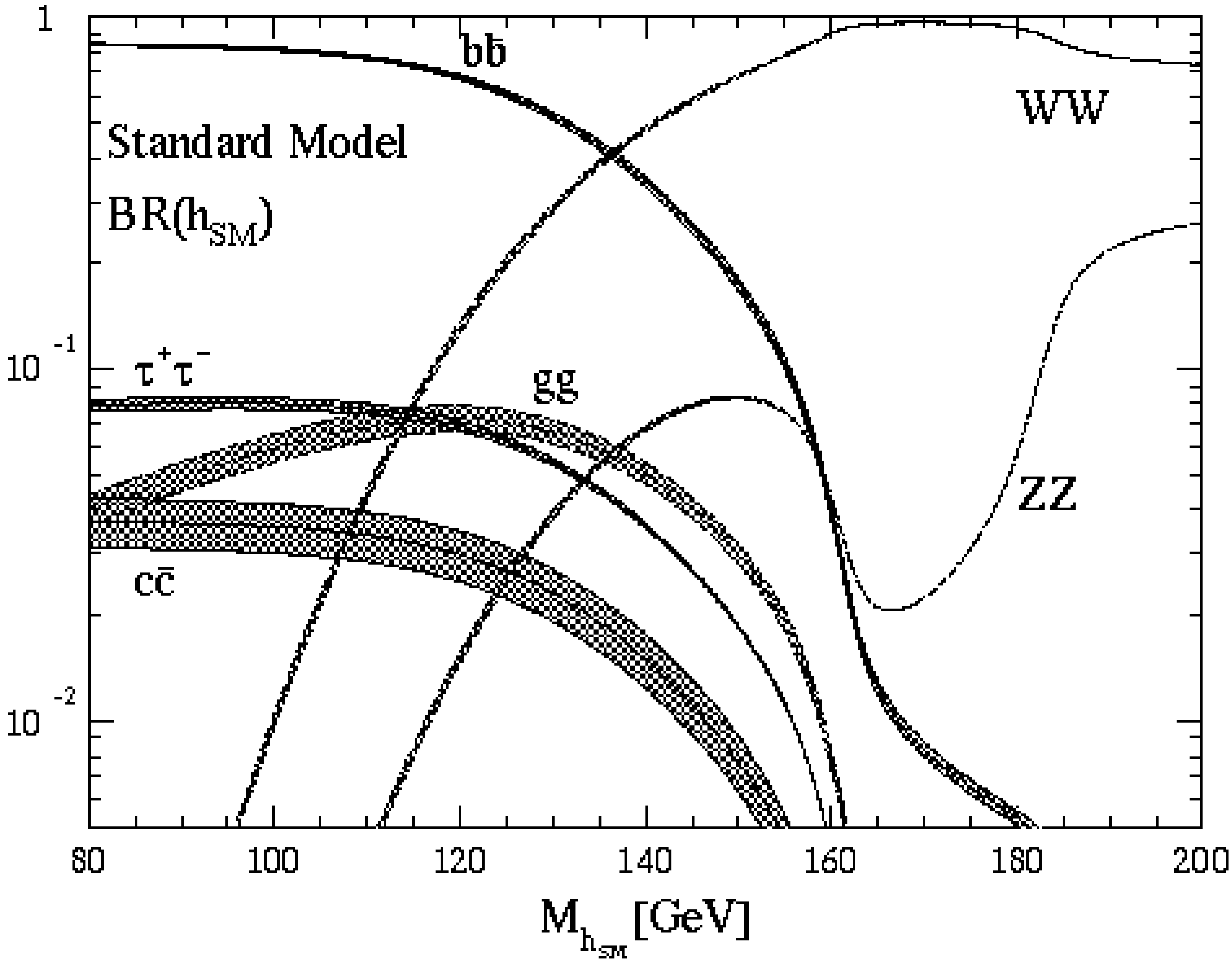


EW Precision => SM Higgs is Light



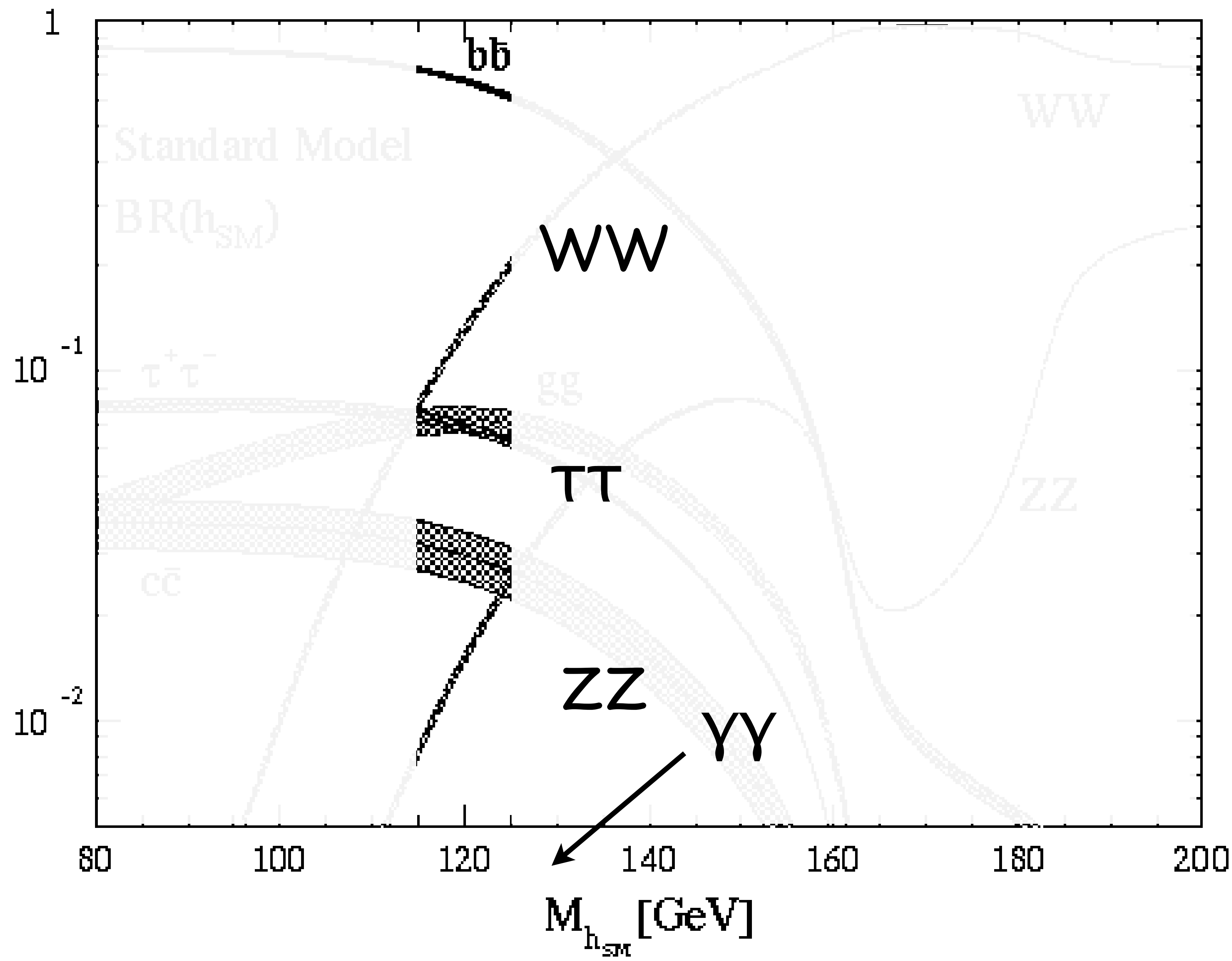


Branching Ratios of SM Higgs

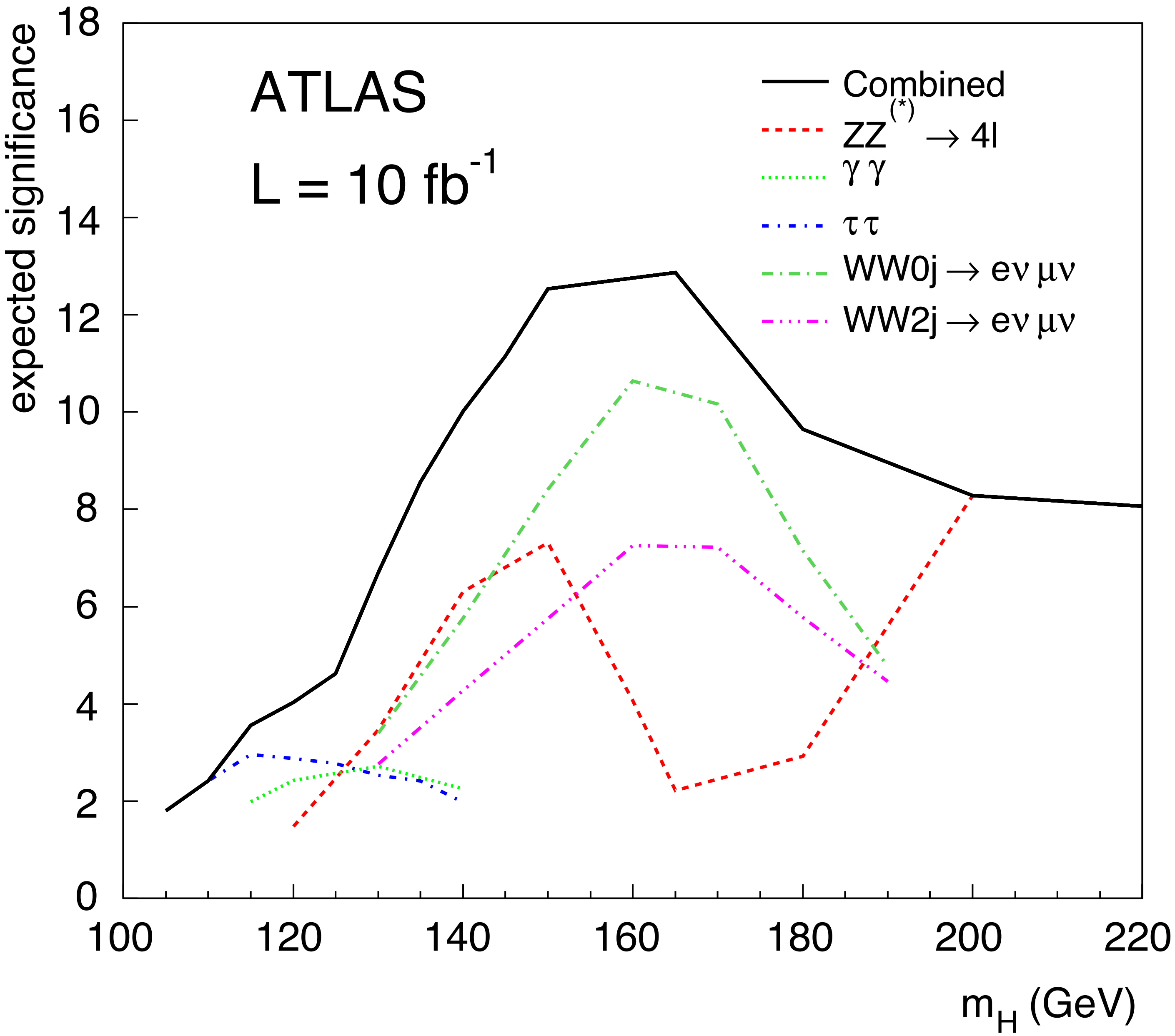


HDECAY

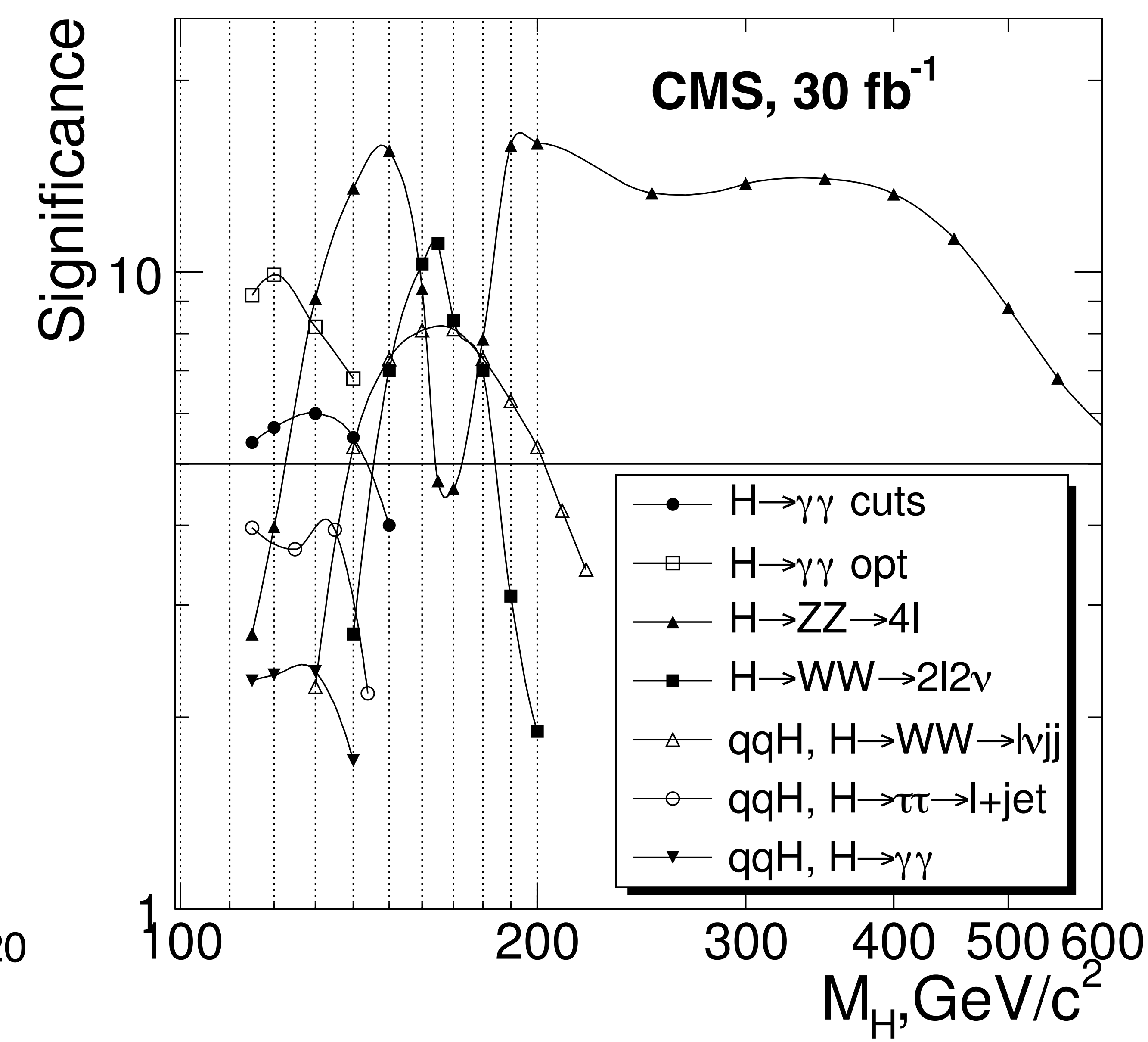
Pesky region is $115 < m_h < 125$ GeV



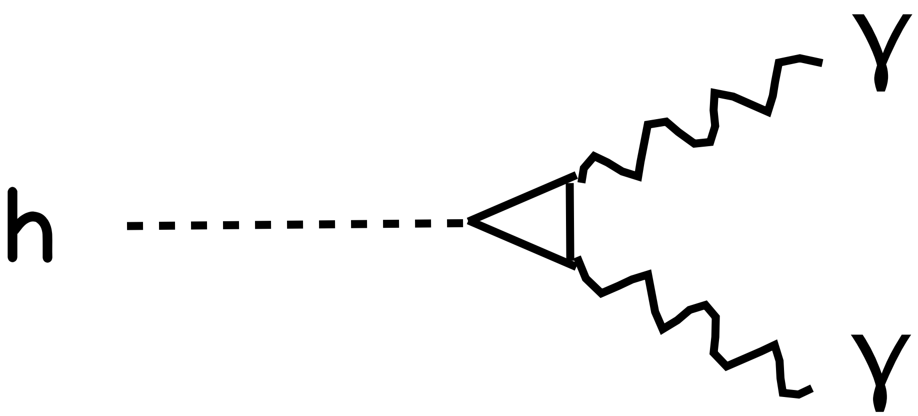
ATLAS TDR 2009
10 fb^{-1}



CMS TDR 2006
30 fb^{-1}

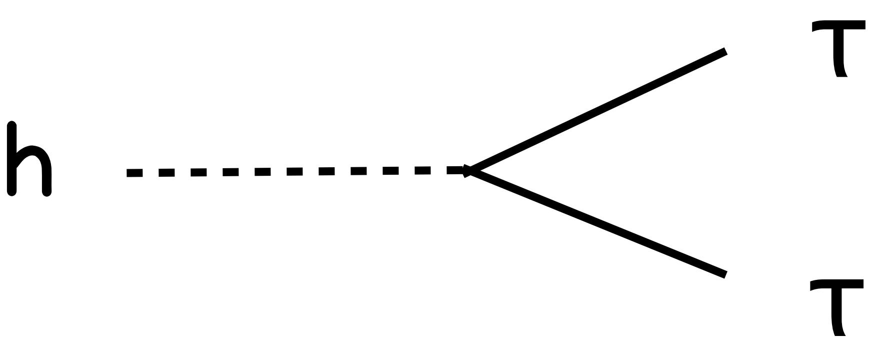


Search Channels 115 < m_h < 125 GeV



BR(h -> γγ) ≈ 1–2 x 10^{-3}

loop suppressed



BR(h -> ττ) ≈ 5–7 x 10^{-2}

$y_\tau \approx 0.01$ suppressed

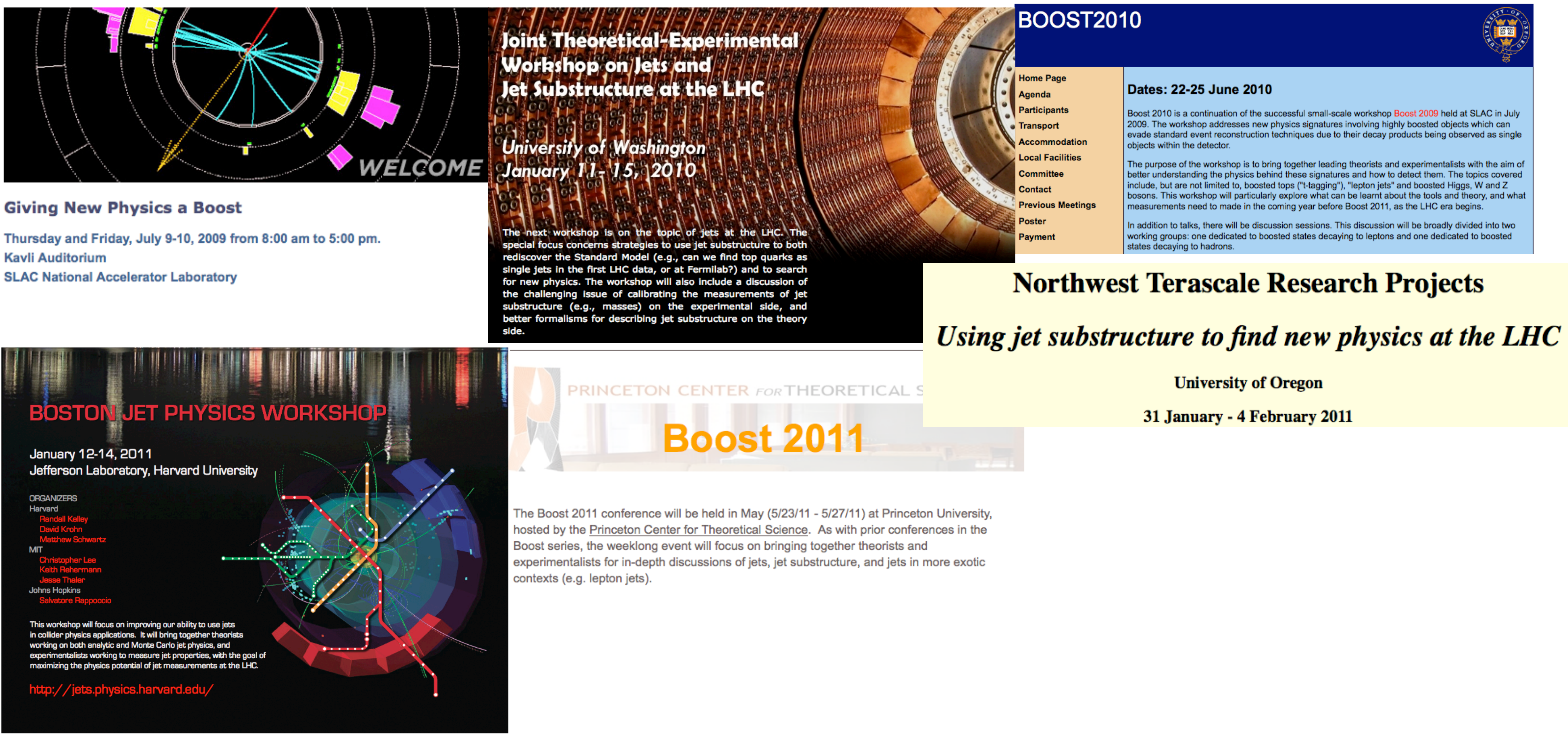
Until 2008, was thought that
BR(h -> bb) ≈ 0.7–0.9
lost in the QCD background.

Outline

- Higgs in Standard Model
- Jet Substructure applied to $h \to b\bar{b}$ @ LHC
- Higgs in new physics:
  i) SUSY
  ii) top-partners
- Discovery of Higgs in new physics events
- Summary

Jet Substructure

Much activity in past 2-3 years...

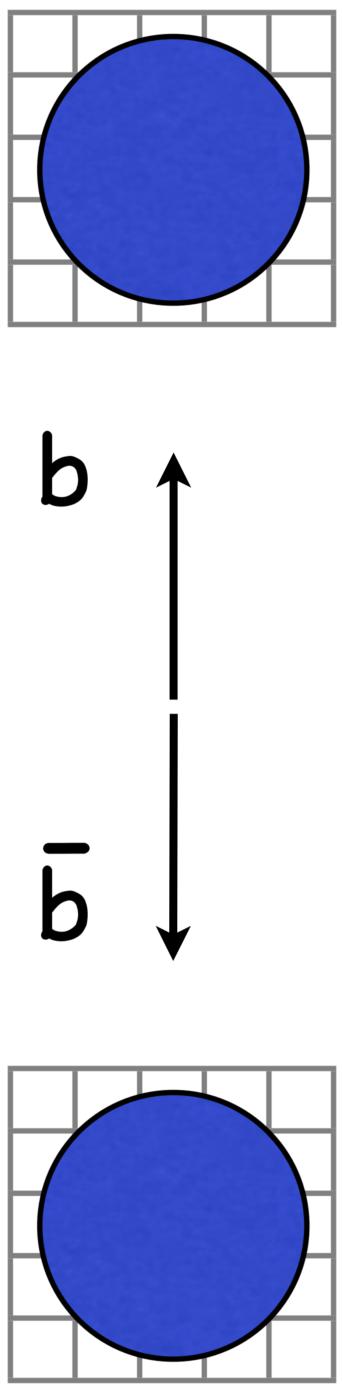


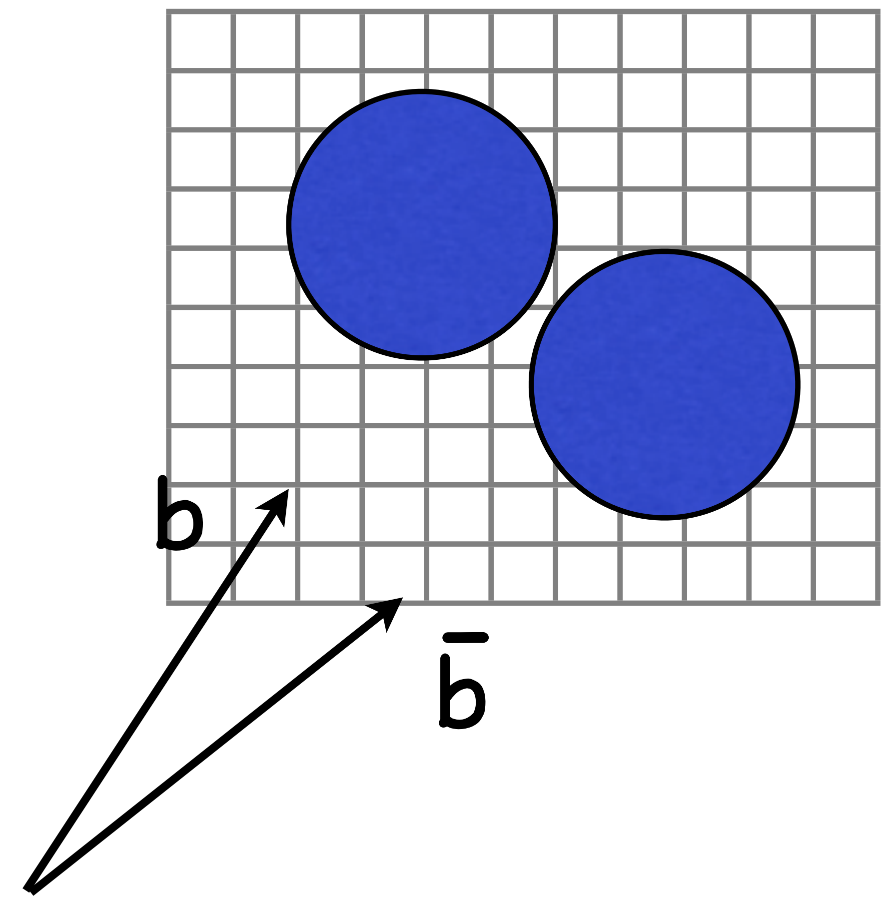
Jet Substructure

Extract more information out of jets.

Enhance $S/\sqrt{B}$ for massive objects decaying to jets over QCD background.
(the boosted advantage)

No Boost versus Boost





$$\Delta R \approx \frac{2\, m_h}{pT}$$

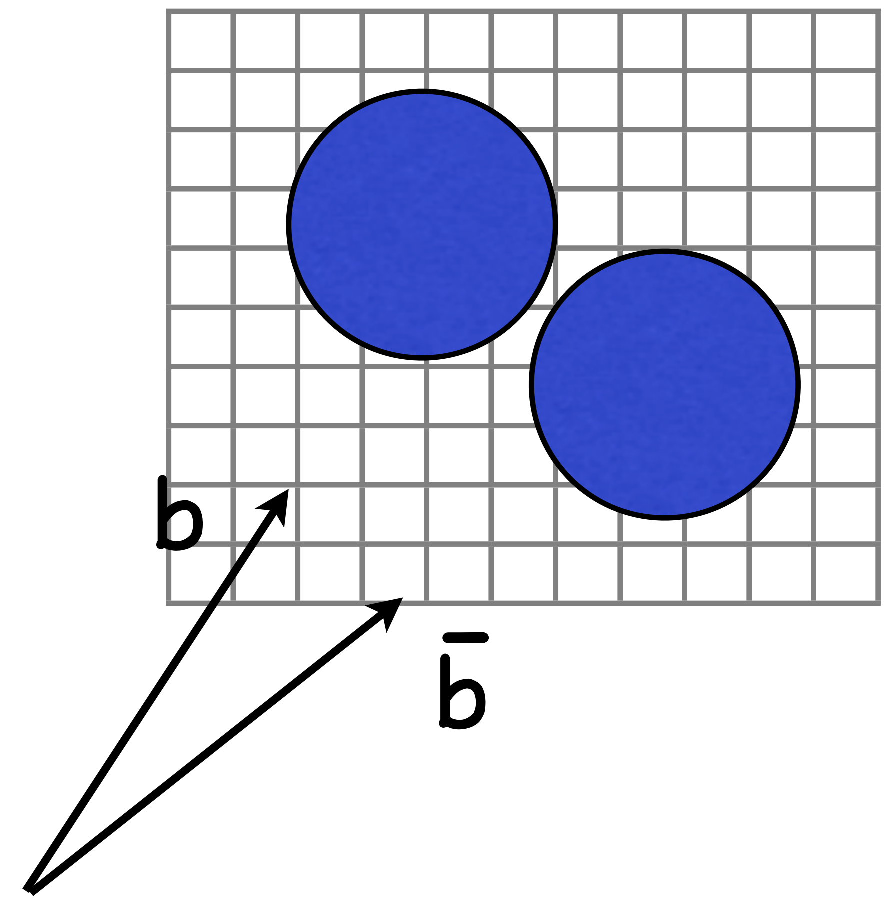
$$R = \sqrt{\Delta y^2 + \Delta \varphi^2}$$

Boosted Higgs Decay

Consider m_h = 120 GeV;

pT > 200-300 GeV

=> $\Delta R \approx 1.2\text{-}0.8$

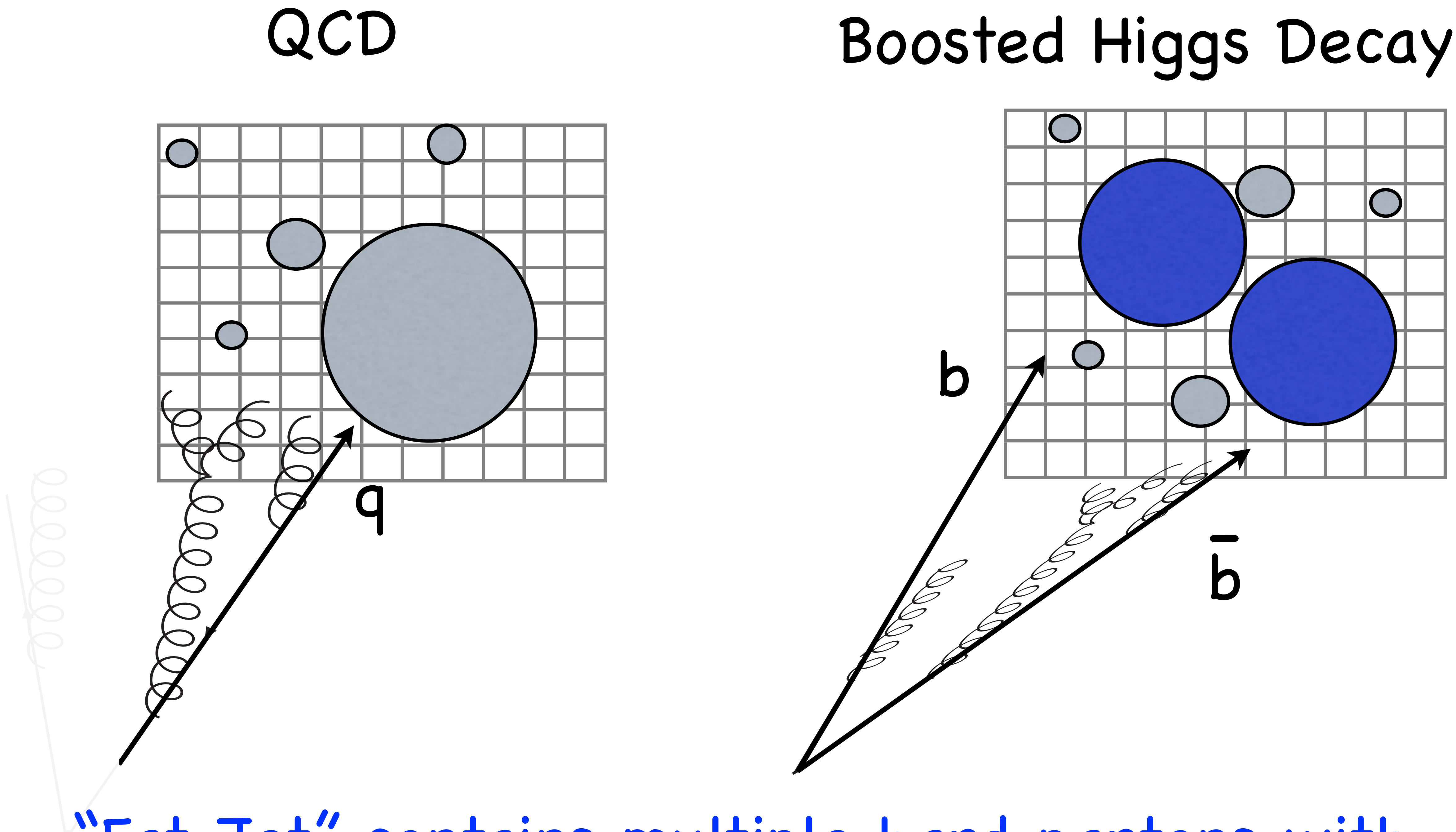


Jet areas begin to overlap!

$$\Delta R \approx \frac{2\, m_h}{pT}$$

$$R = \sqrt{\Delta y^2 + \Delta\varphi^2}$$

Advantage over Backgrounds



"Fat Jet" contains multiple hard partons with distinguishable kinematic properties

Jet Substructure and Filtering

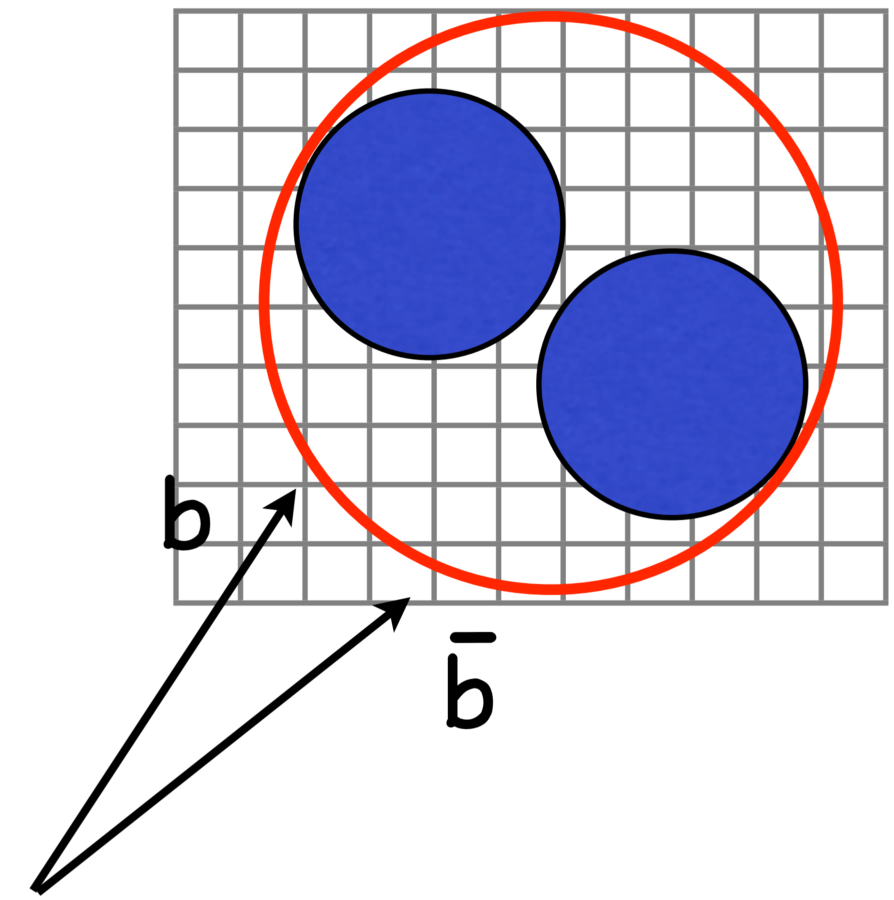
Butterworth, Davison, Rubin, Salam [BDRS: 0802.2470] proposed a set of techniques to find h -> $b\bar{b}$ by precisely exploiting the $S/\sqrt{B}$ advantages of "fat jets".

The basis of their techniques involves using an iterative jet clustering algorithm (C/A), examining subjet kinematics step-by-step, and finally choosing the "best" subjets from which to form the fat jet mass.

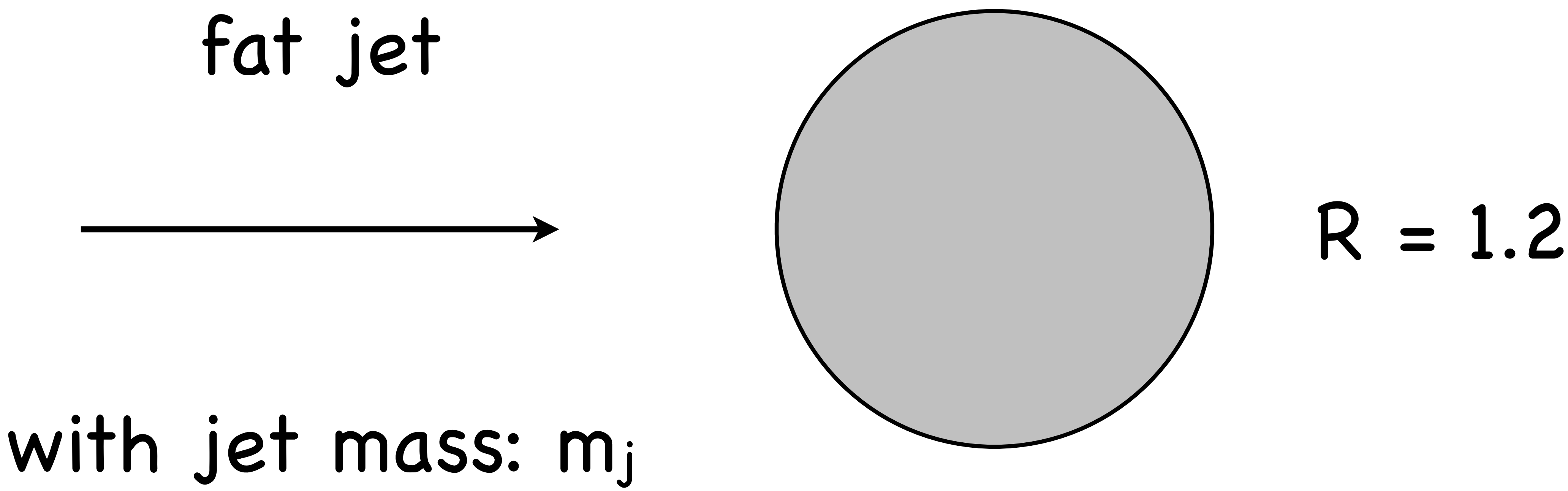
Fat Jets

$$\text{Given } \Delta R \approx \frac{2\, m_h}{p_T} = 1.2 \; \frac{m_h}{120\ \text{GeV}} \; \frac{200\ \text{GeV}}{p_T}$$

Let C/A clustering algorithm proceed up to R = 1.2, to capture both b jets into one fat jet, requiring pT > 200 GeV.

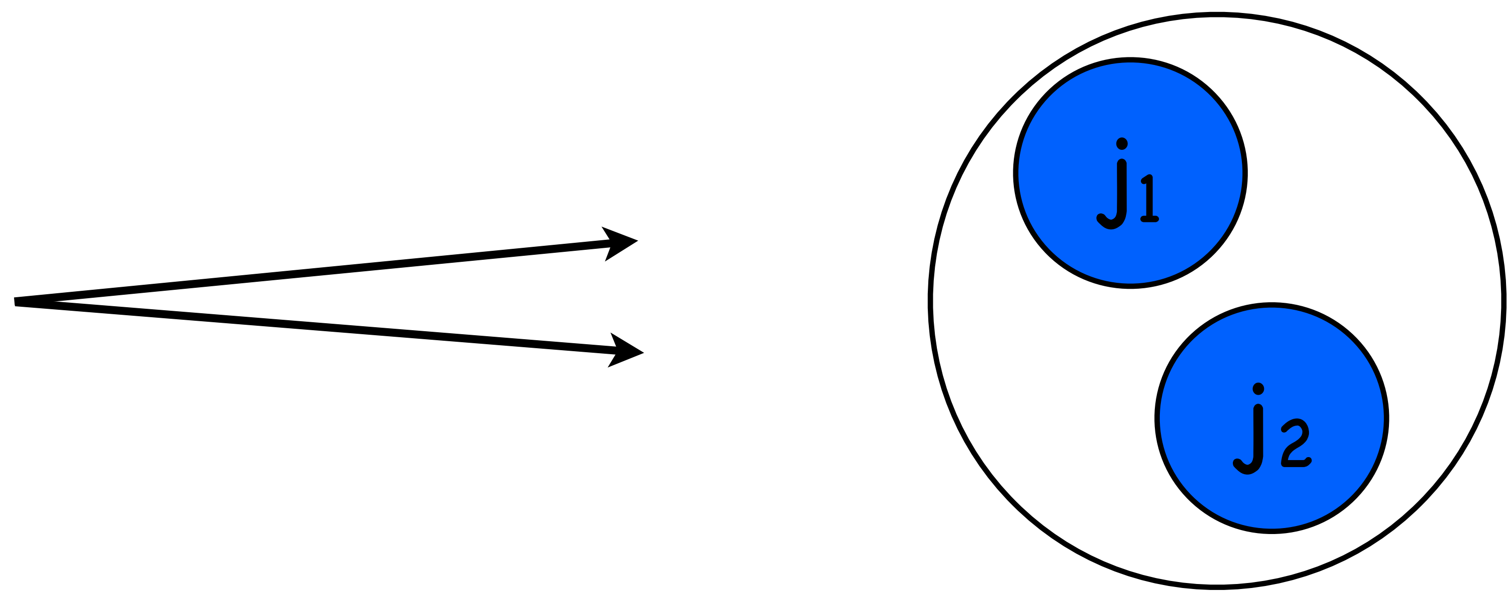


Jet Decomposition Cartoon



Jet Decomposition Cartoon

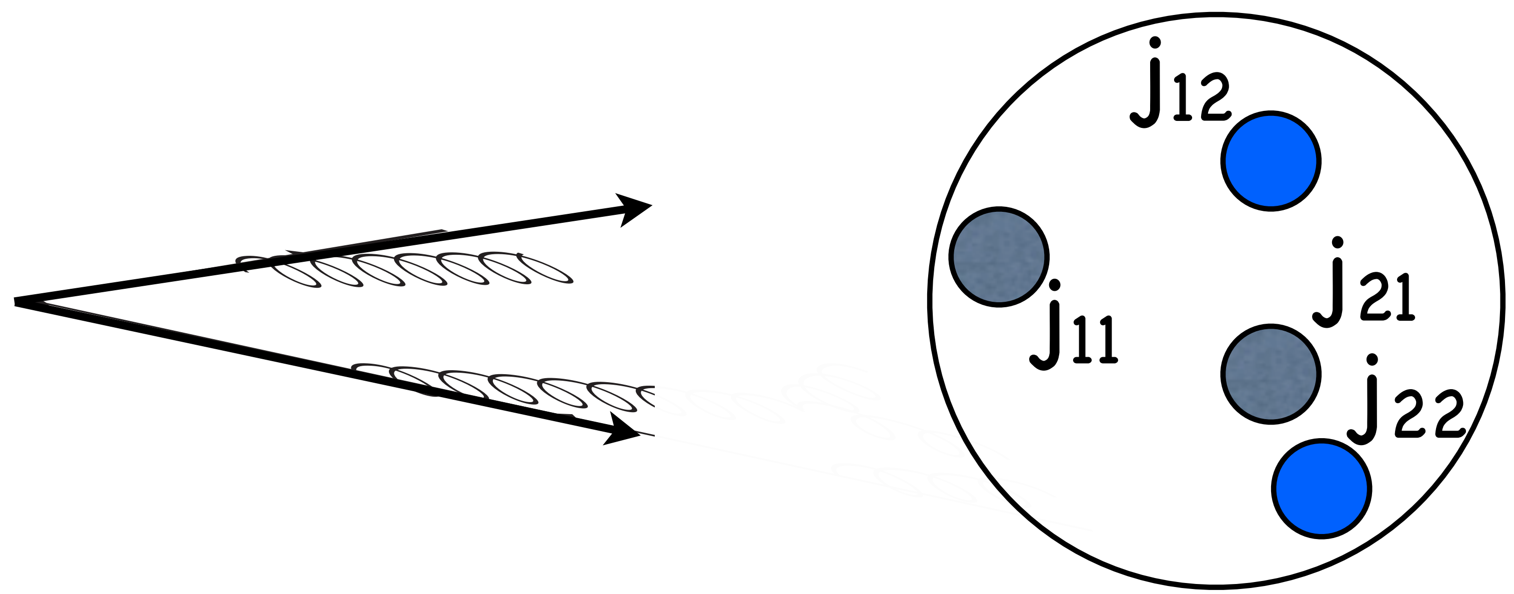
undo clustering



In C/A, this came from two jets with jet masses $m_{j1} > m_{j2}$

Jet Decomposition Cartoon

repeat unclustering:



four jets with masses: $m_{j11} > m_{j12}$, $m_{j21} > m_{j22}$

Higgs Jet Identification

1) check for "mass drop"

$m_{j1} < 0.68\ m_j$?

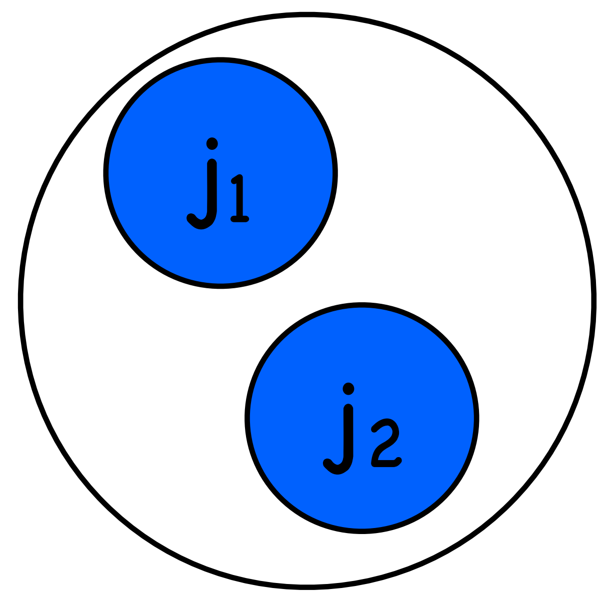
Expect drop for heavy particle decay

2) check "asymmetry"

$$y = \frac{\min\left(p_{t_{j1}}^2, p_{t_{j2}}^2\right)}{m_j^2} \Delta R_{j_1,j_2}^2 > y_{\mathrm{cut}}$$

$y_{cut} = (0.3)^2$

Tends to reject soft/colinear QCD contamination

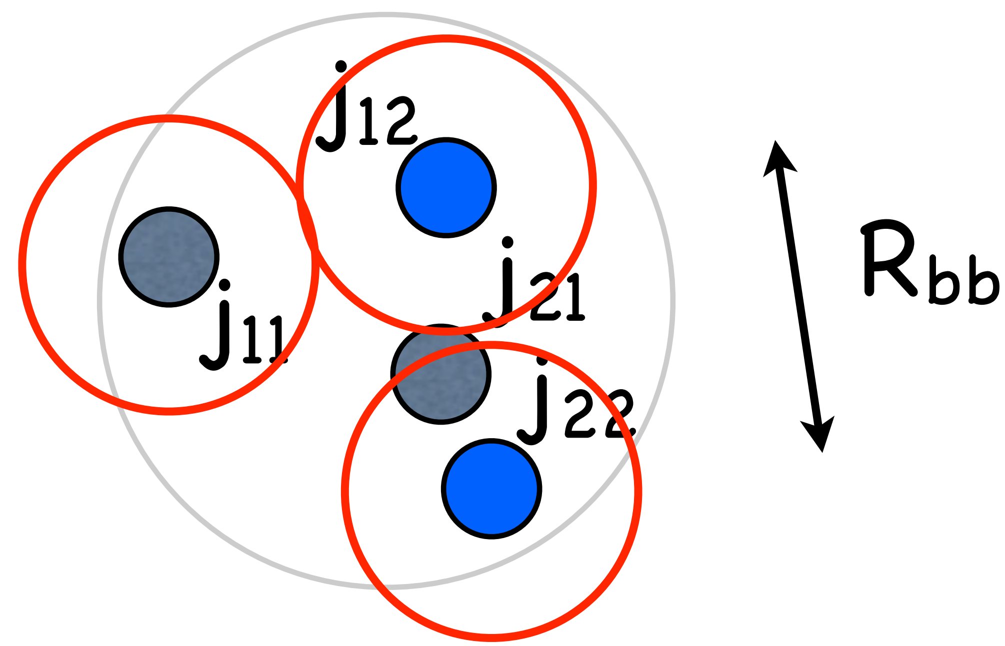


3) require both subjets b-tagged

Filtering

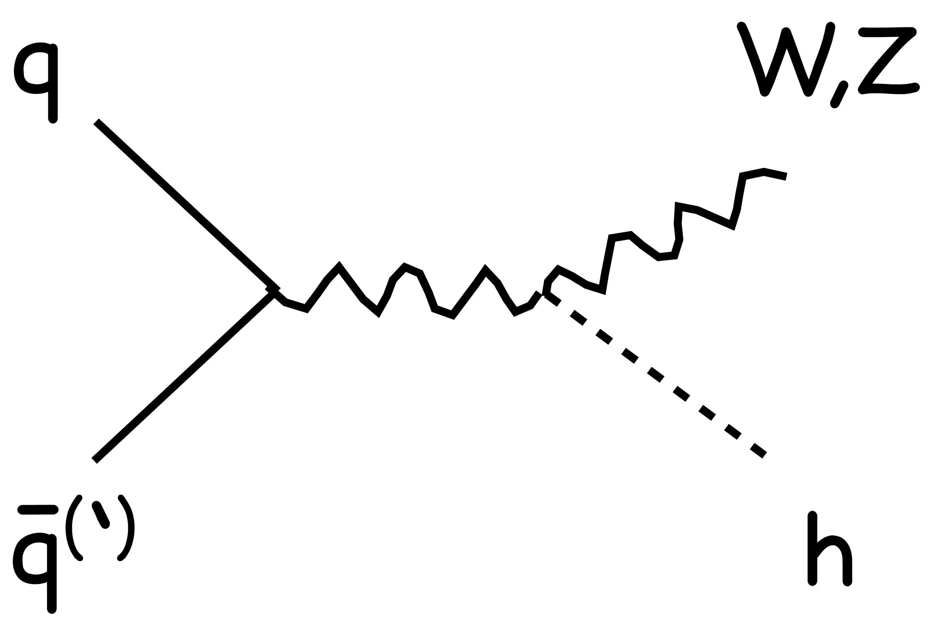
4) Filter the subjets to reduce underlying event contamination:

- take 3 highest pT subjets ("third" captures leading parton shower gluon)
- recluster subjets with $R_{j1,j2,j3} = \min(R_{bb}/2, 0.3)$



Higgs Candidate Mass formed from
3 highest pT subjets

Production: Higgs-strahlung

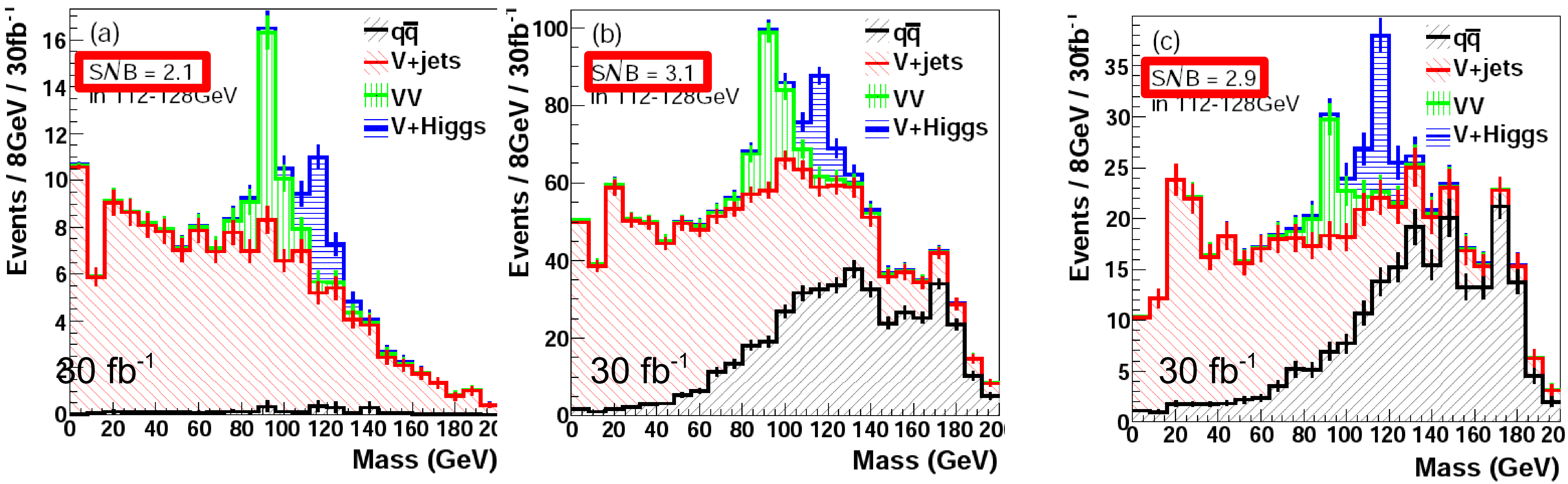


Require Higgs is boosted
pT(h) > 200 GeV
(only 5% of Zh/Wh cross section
@ 14 TeV)

Leptonic decay of W/Z into
llbb, lνbb, ννbb.

BDRS Result

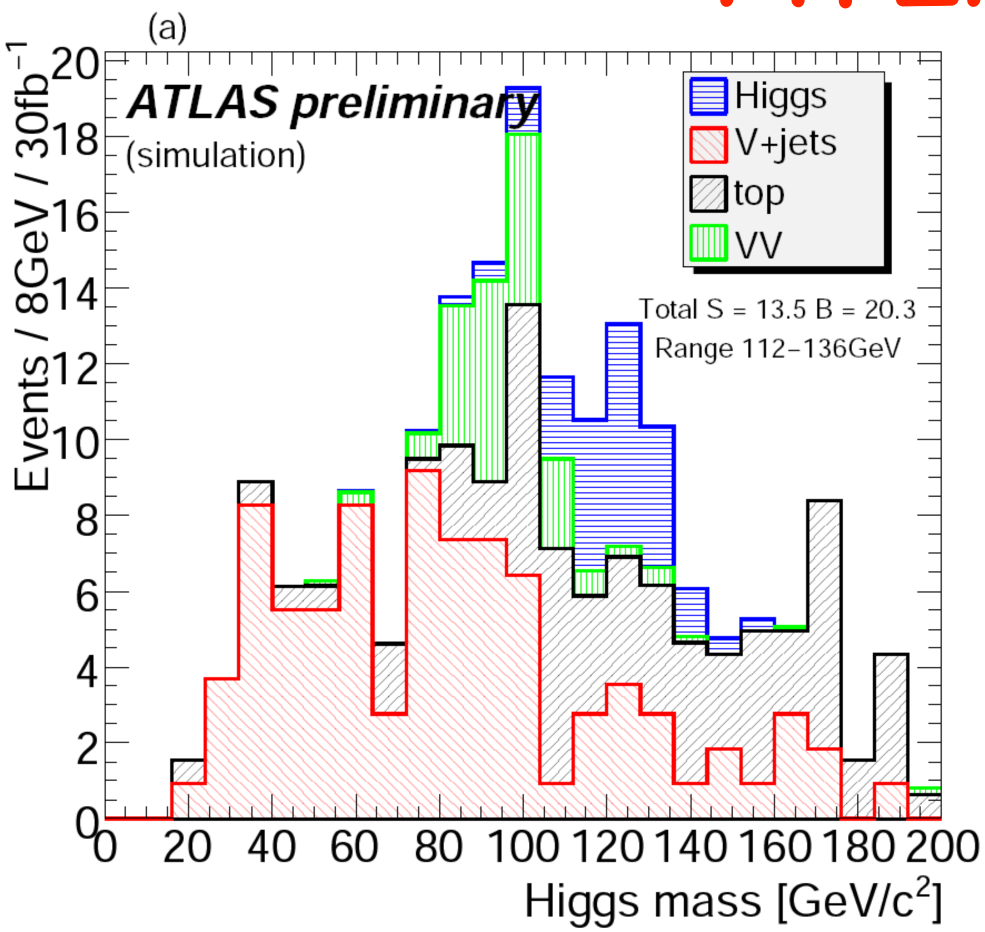
llbb lνbb ννbb



- LHC 14 TeV; 30 fb^{-1}; mh = 115 GeV
- HERWIG/JIMMY
  cross-checked with PYTHIA with “ATLAS tune”
- 60% b-tag; 2% mistag
- no smearing

BDRS 0802.2470

ATLAS Simulation



The WH (W→lν,H→bb) analysis: cut flow (main signal and backgrounds samples)

L=30 fb^{-1}

Loose jet veto and loose b-tagging (to be used as input to likelihood fit):

	WH(120)	WZ	$t\bar{t}(p_T^{min})$	Wt	W+jets
After filter cuts	1252.8 ± 7.8	9331	1609356	169519	2433885
1 Higgs candidate	569.7 ± 3.0	3509.7 ± 8.0	806175	69375	562030
filtered $p_T > 200$ GeV	512.7 ± 3.2	3108 ± 10	709271	60241	413406
Missing $E_T > 30$ GeV	362.4 ± 3.2	2183 ± 13	552284	46779	318400
p_T(W) > 200 GeV	171.0 ± 2.6	1216 ± 12	137946	18524	206331
$p_T(e/\mu)$>30 GeV	145.6 ± 2.4	996 ± 11	115053	15724	178004
p_T(additional μ)<10 GeV	144.6 ± 2.4	942 ± 11	106836	14992	177542
p_T(additional e)<10 GeV	142.9 ± 2.4	885 ± 11	97305	13881	174941
$\Delta\phi$(W,H) > $\frac{2}{3}\pi$	142.2 ± 2.4	841 ± 11	84773	12999	167704
no additional b-jets p_T >15 GeV	130.6 ± 2.3	790 ± 10	30605	7805	160608
add. jets on W side p_T <60 GeV	115.7 ± 2.2	637.2 ± 9.5	19422	5870	121437
add. jets on H side p_T <60 GeV	102.7 ± 2.1	525.6 ± 8.8	13841	4370	94055
one subjet b-tagged	91.4 ± 2.0	126.1 ± 4.5	8638	2421	6964
both subjets b-tagged	45.6 ± 1.4	43.7 ± 2.7	576	161.4 ± 7.0	266
loose fit cuts	45.4 ± 1.4	43.0 ± 2.7	565	156.3 ± 6.9	257

Tight jet veto and tight b-tagging at ε_b~63 % and c(l)=0.2 (for counting based analysis)

	WH(120)	WZ	$t\bar{t}(p_T^{min})$	Wt	W+jets
add. jets on W side p_T <20 GeV	83.2 ± 1.9	461.3 ± 8.3	7227	3343	86087
add. jets on H side p_T <20 GeV	55.8 ± 1.6	275.6 ± 6.6	1895	1142	48229
one subjet b-tagged	46.4 ± 1.5	49.8 ± 2.9	986	498 ± 12	1825
both subjets b-tagged	19.51 ± 0.96	16.5 ± 1.7	38.9 ± 4.9	18.2 ± 2.4	87.3 ± 9.0
112 GeV < mass(H) < 136 GeV	13.25 ± 0.79	1.18 ± 0.45	5.6 ± 1.9	4.2 ± 1.1	8.3 ± 2.8

Signal events (m_H~120 GeV): ~13.5

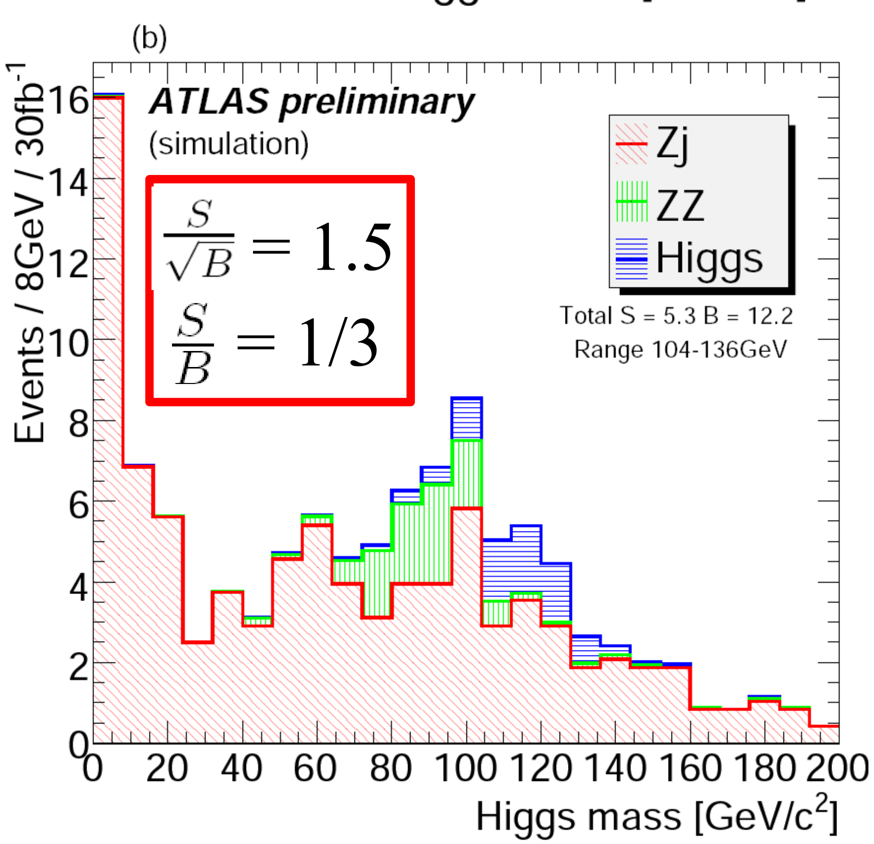
Background events: ~20.3

$$\frac{S}{\sqrt{B}} = 3.0 \pm 0.3$$

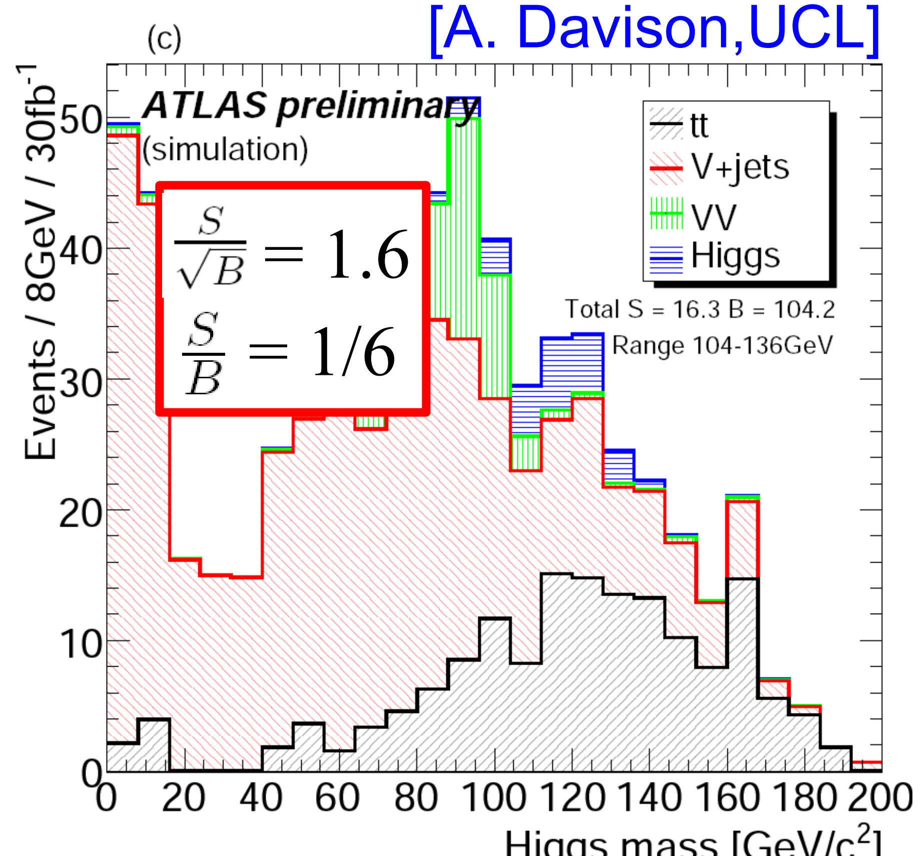
Giacinto Piacquadio

[A. Davison,UCL]

llbb



ννbb



ATL-PHYS-PUB-2009-088 (Aug 2009)

Strongly Motivating!

- background uncertainty

Channel	signal	t_i	w_i	z_i	$S/\sqrt{B}$
$llb\bar{b}$	5.34	0.98	0.0	11.2	1.5
$l\nu b\bar{b}$	13.5	7.02	12.5	0.78	3.0
$\nu\nu b\bar{b}$	16.3	45.2	27.4	31.6	1.6
Combined					3.7

σ_t	σ_w	σ_z	Significance
Perfect	Perfect	Perfect	3.7
5%	5%	5%	3.5
10%	10%	10%	$\boxed{3.2}$
15%	15%	15%	$\boxed{3.0}$
20%	20%	20%	2.8

- **10/15 %** uncertainty considered as realistic:
  - Median discovery significance: **3.0-3.2**

- b-tagging efficiency (better for subjets!)

- underlying event

- pile-up; at 10^{34} $cm^{-2}s^{-1}$ mass resolution of Higgs degraded with C/A; more elaborate techniques?

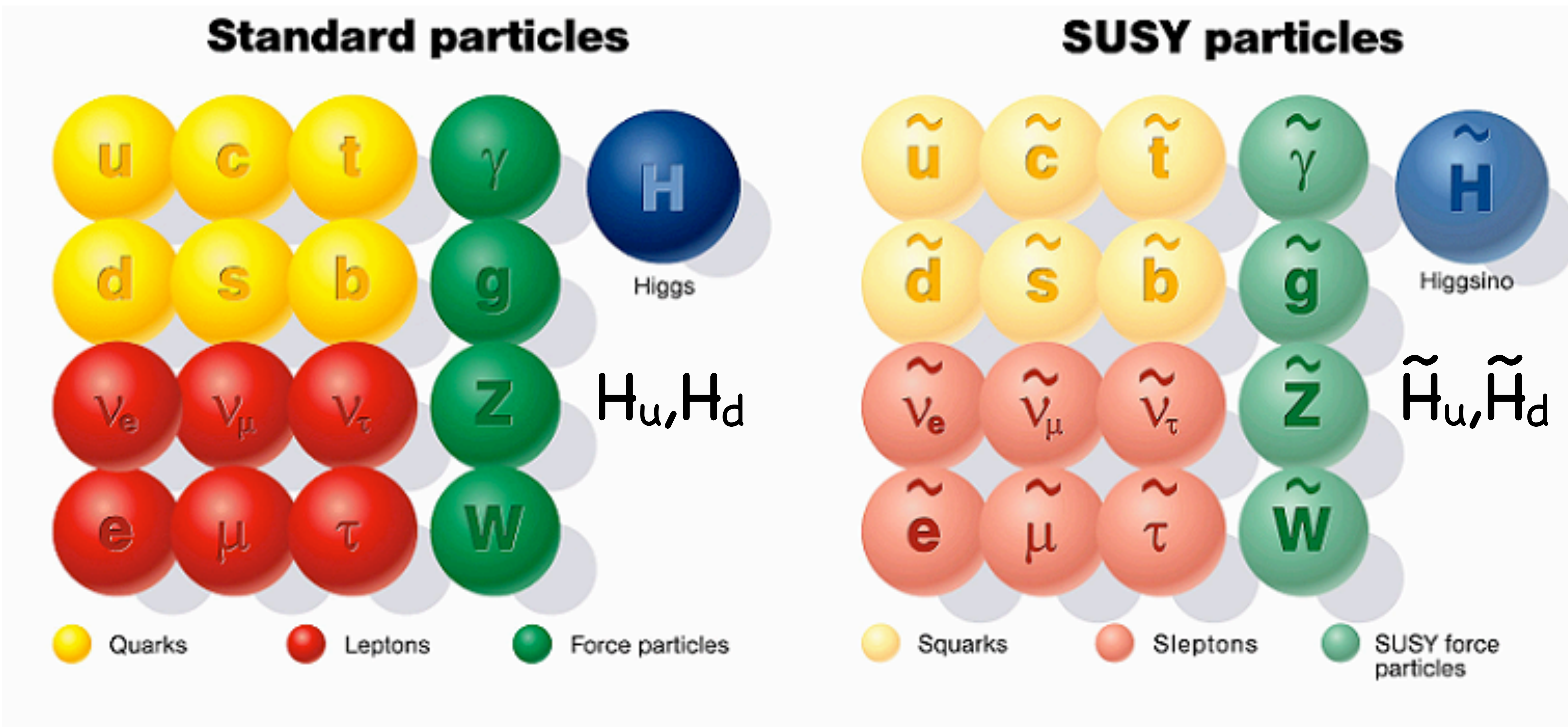
Outline

- Higgs in Standard Model
- Jet Substructure as tool to find $h \to b\bar{b}$ @ LHC
- Higgs in new physics:
  i) SUSY
  ii) top-partners
- Discovery of Higgs in new physics events
- Summary

Outline

- Higgs in Standard Model
- Jet Substructure as tool to find $h \to b\bar{b}$ @ LHC
- Higgs in new physics:
  i) SUSY
  ii) top-partners
- Discovery of Higgs in new physics events
- Summary

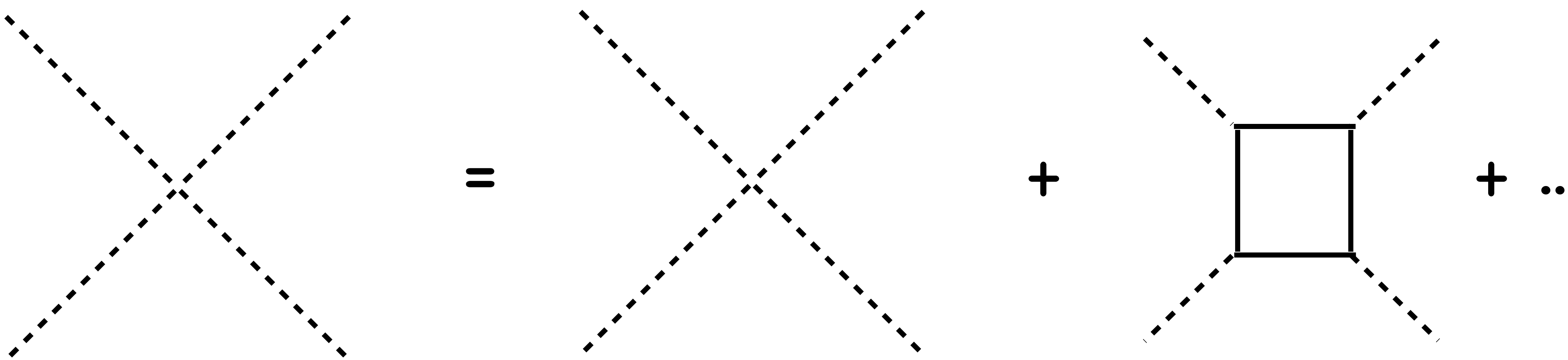
Weak Scale Supersymmetry



"Minimal Supersymmetric Standard Model (MSSM)"

Higgs Sector of MSSM

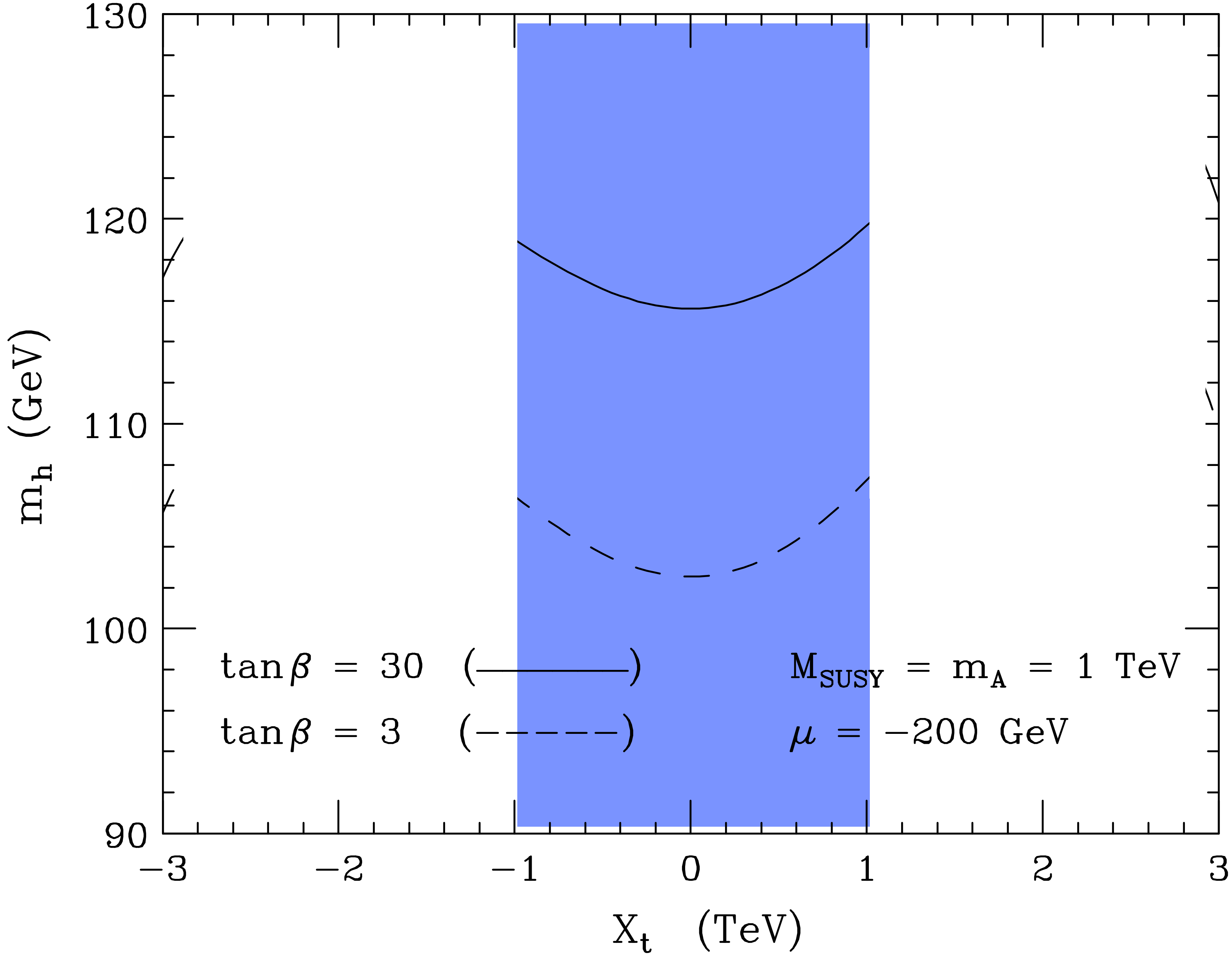
quartic coupling λ — **determined!** $g^2 + (g')^2$ — up to radiative corrections



$$m_h^2 = M_Z^2 \left(\frac{\tan^2\beta - 1}{\tan^2\beta + 1} \right)^2 \quad + \quad y_t^4 \log m_{st}/m_t$$

(schematic)

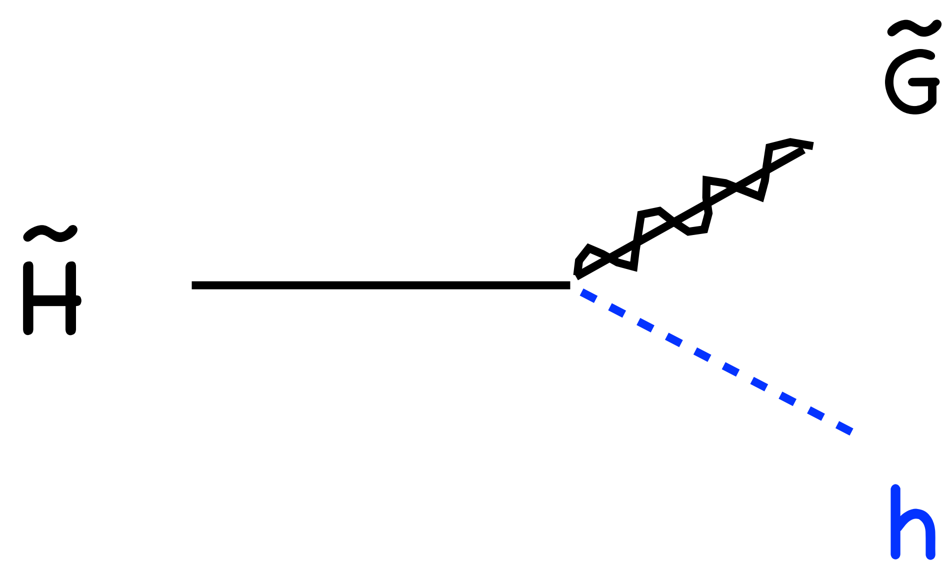
h is light



Carena, Haber Higgs report 2002

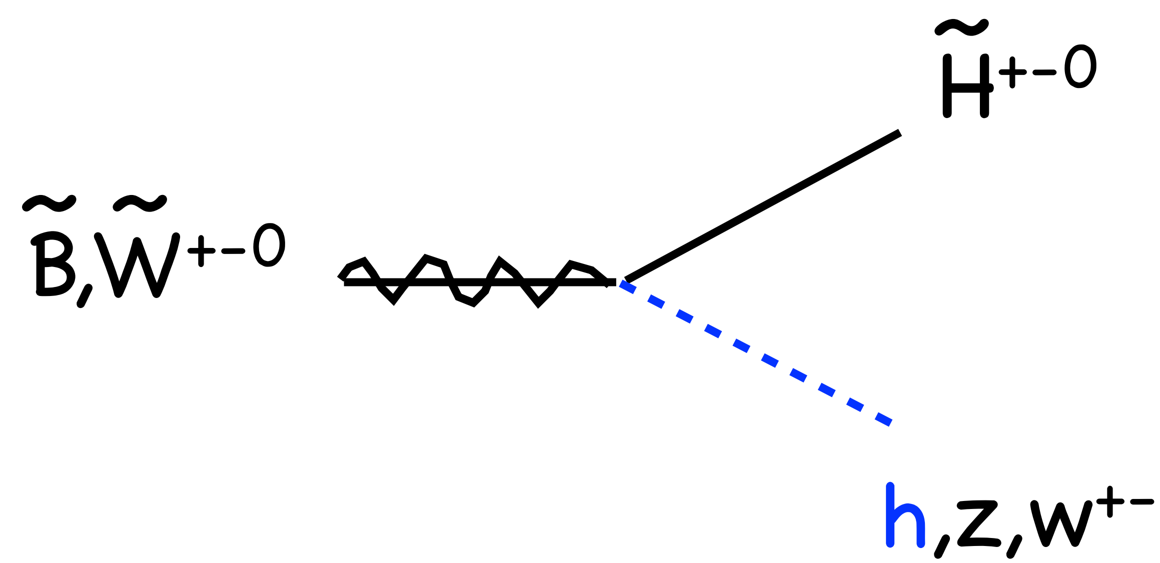
Superpartner Decay to Higgs

SUSY with a gravitino LSP and Higgsino NLSP:



BR up to 50%

SUSY with a Higgsino LSP:



BR ≈ 25%

Kinematical requirement

$\mu > m_{\tilde{G}} + m_h$

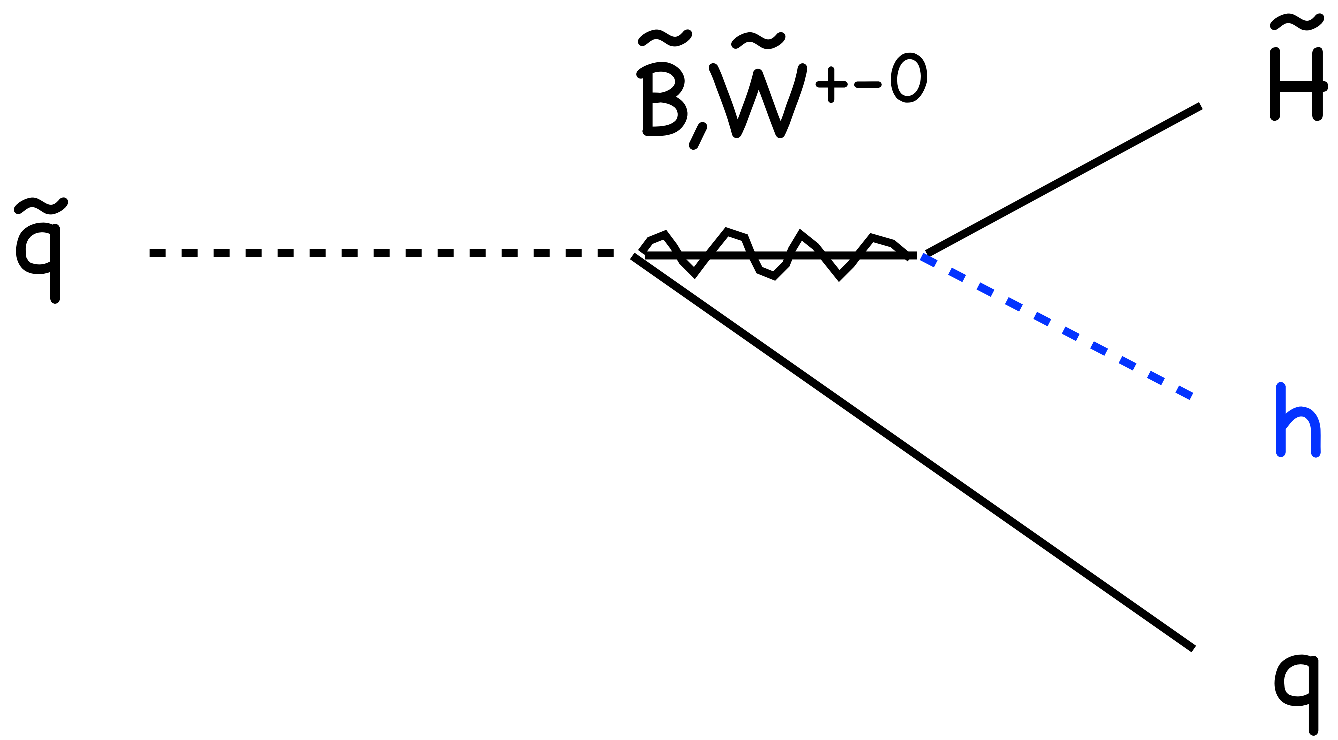
> 120 GeV

$m_{Wino} > \mu + m_h$

$> 100 + 120 = 220$ GeV

Squark Production to Gauginos

(which then decay to Higgs)



typical $\sigma(\text{squarks})_{14\ \text{TeV}} \approx$ several pb!!

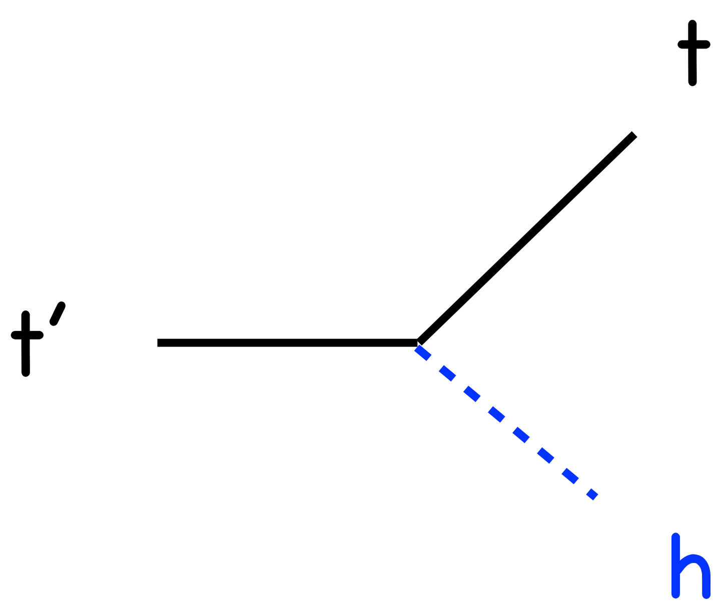
Outline

- Higgs in Standard Model
- Jet Substructure as tool to find $h \to b\bar{b}$ @ LHC
- Higgs in new physics:
  i) SUSY
  ii) top-partners
- Discovery of Higgs in new physics events
- Summary

Top Partners

little Higgs models, top color, ...

Vector-like pair of quarks $T(3,1,2/3)$, $\bar{T}(\bar{3},1,-2/3)$



"Goldstone region"
for $m(t') \gg m(t)$
$\approx$ 25% of time decay
to h
$\approx$ 75% of time to
longitudinal W/Z

Kinematical requirement

$$m_{t'} > m_t + m_h$$
$$> 175 + 120 = 295 \text{ GeV}$$

Key Advantages of New Physics Source

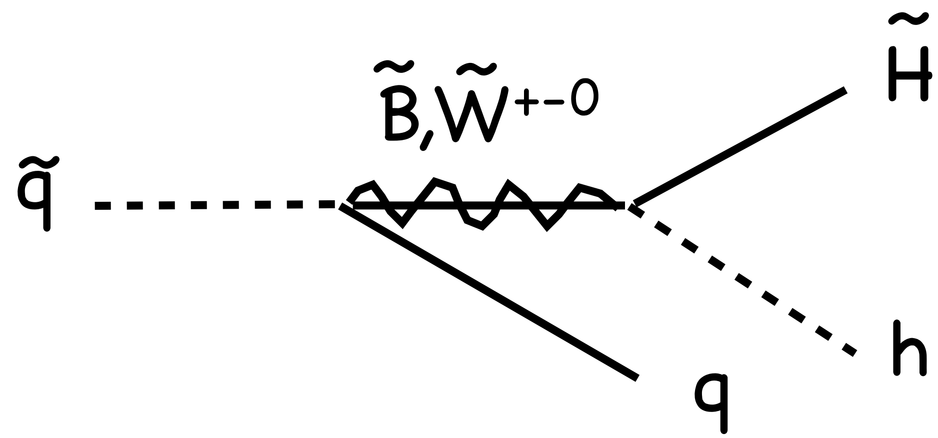
- Production source can be QCD (enhanced!)
- Cascade decays from heavy new particles leads to significant boost for a large fraction of events
- In MSSM, Higgs is always light

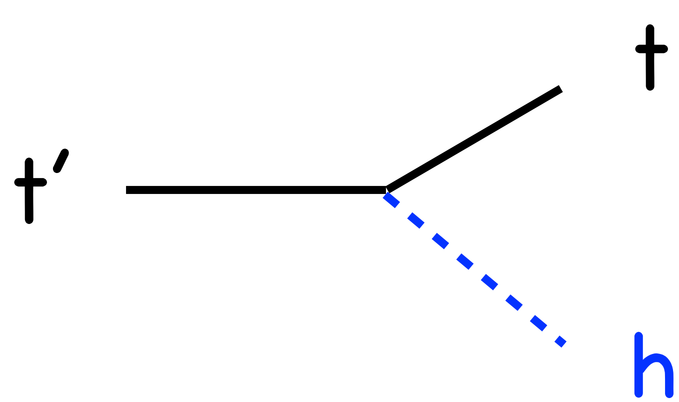
(in other models, lighter Higgs consistent with EW precision data)

Outline

- Higgs in Standard Model
- Jet Substructure applied to h -> $b\bar{b}$ @ LHC
- Higgs in new physics:
  i) SUSY
  ii) top-partners
- Discovery of Higgs in new physics events
- Summary

New Physics Production -- Busy Events!





New physics events tend to be "busy" with a lot of hadronic activity from squark/gluino/top-partner decay and associated parton showers.

Can have extra hard subjets in "fat jet" cone!

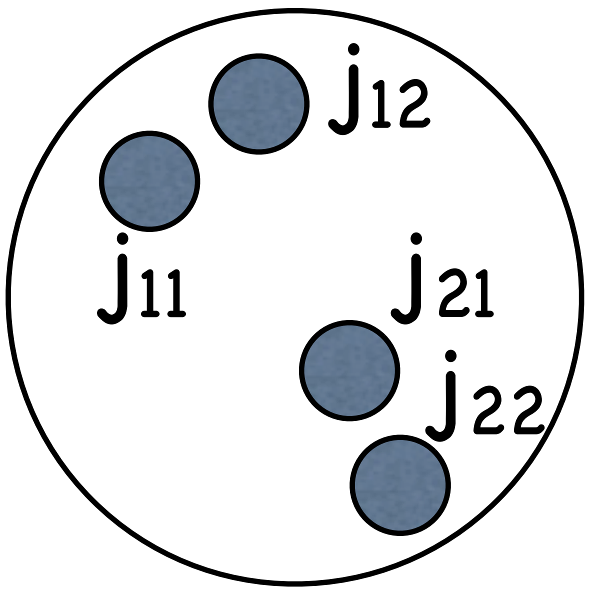
Similar problem also with t,tbar,h!

Plehn, Salam, Spannowsky

Our New Step
Search Jet Daughters for Maximal "Similarity"

At each stage of unclustering, calculate "similarity":

$$S_i = \frac{\min\left(p_{t_{j_1}}^2, p_{t_{j_2}}^2\right)}{\left(p_{t_{j_1}} + p_{t_{j_2}}\right)^2} \Delta R_{j_1 j_2}$$



Choose 3 highest pT jets from stage which maximizes "S"

This helps improve the efficiency of finding the Higgs by ≈ 10-20% by not rejecting fat jets with stray b-tagged jet.

Simulation details...

Background: ALPGEN $\longrightarrow$ PYTHIA6.4

Signal: SUSPECT2 $\longrightarrow$ PYTHIA6.4

underlying event:
ATLAS tune

- All final-state hadrons grouped into cells of size $(\Delta\eta \times \Delta\phi) = (0.1 \times 0.1)$
- Each cell is rescaled to be massless

this models detector response (Thaler, Wang '08)

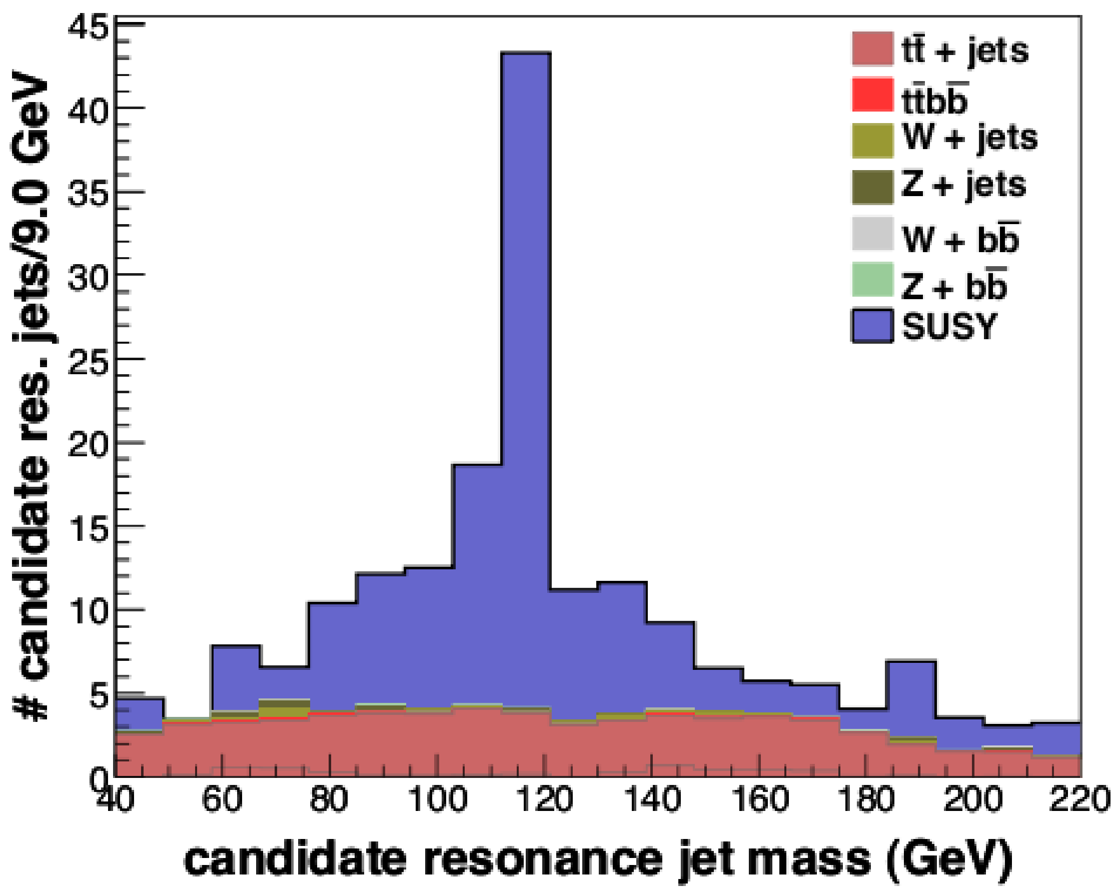
jet gymnastics performed using FastJet (hep-ph/0512210)

b-tagging: 60% efficiency, 2% fake rate

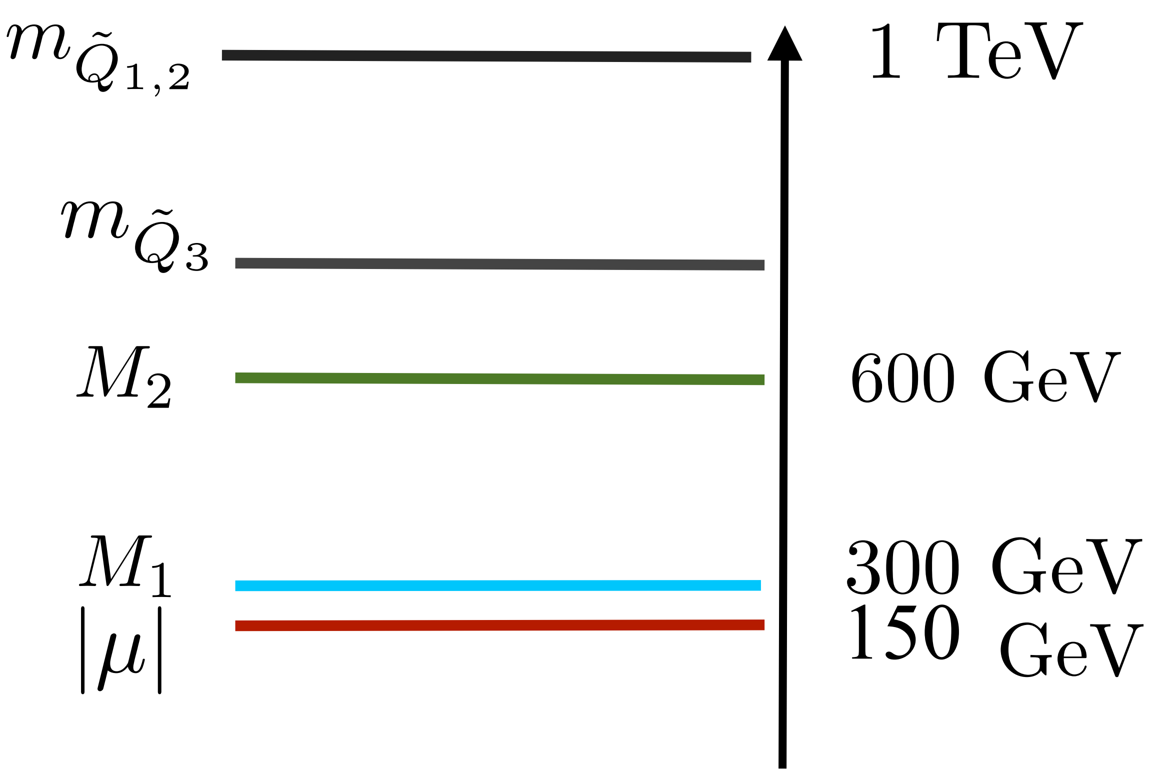
jet-photon fake rate: $.1\%$

Example 1: MSSM with Higgsino LSP

$10\ fb^{-1}$ @ 14 TeV



GK, Martin, Roy, Spannowsky; 1006.1656



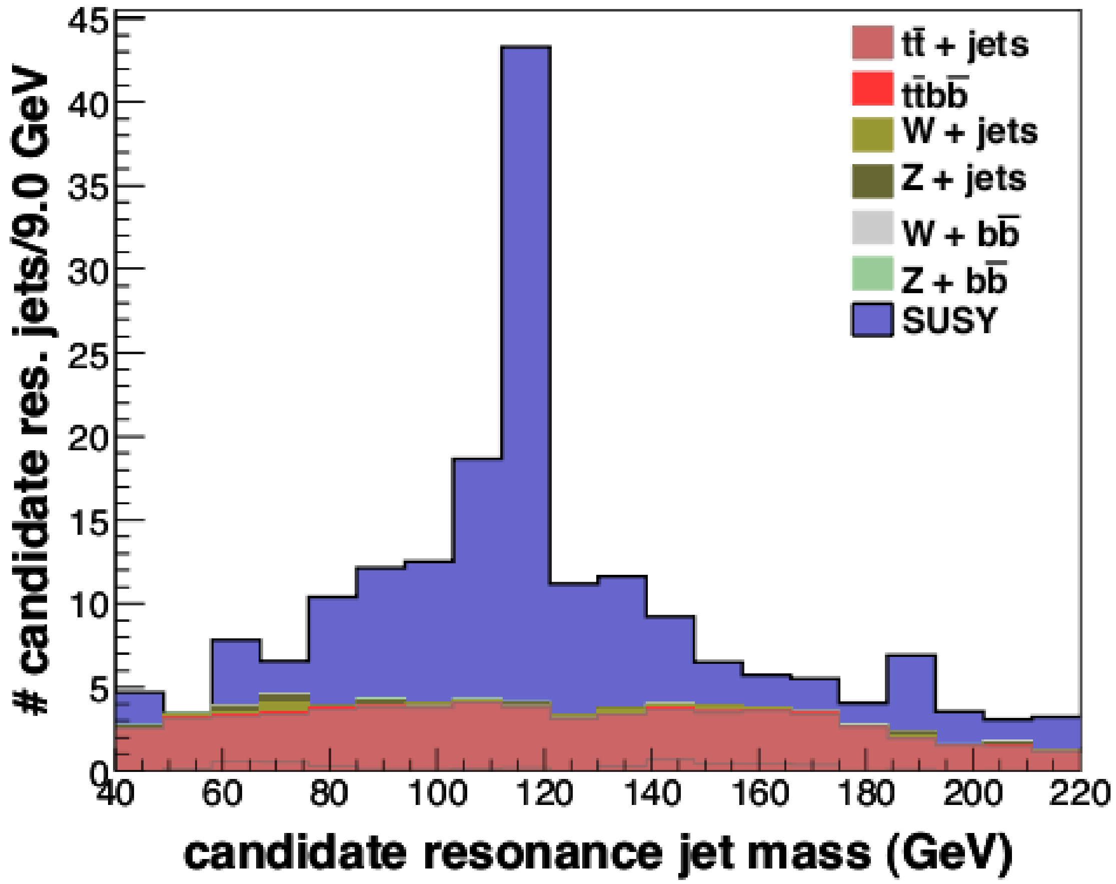
$$BR(\tilde{u}_L, \tilde{d}_L \to h + X) \sim 23\%$$
$$BR(\tilde{u}_R, \tilde{d}_R \to h + X) \sim 16\%$$

MET > 300 GeV, H_T > 1 TeV, 3+ jets,

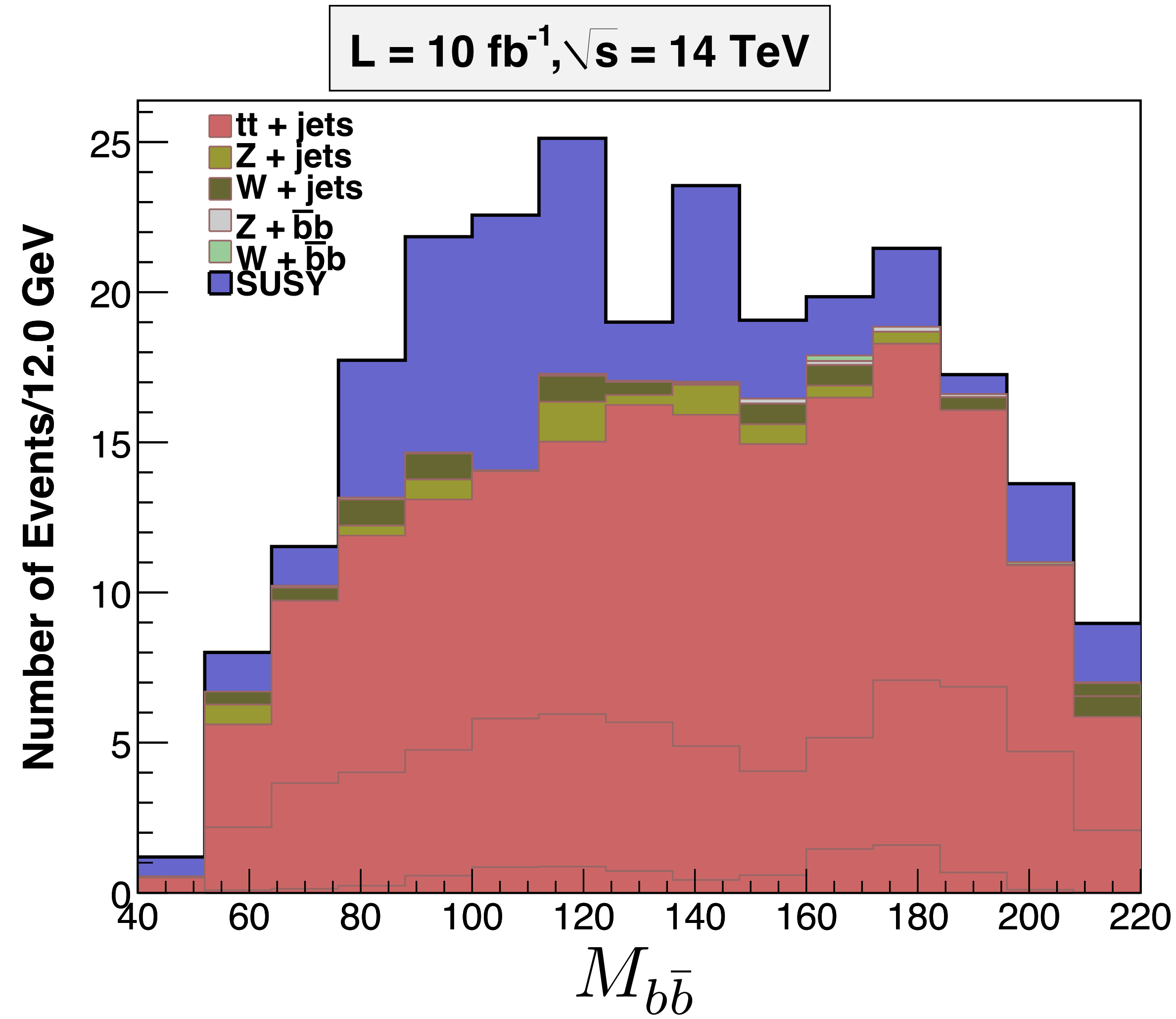
no lepton, + 1 "tagged" Higgs

"What good is that fancy substructure?"

Comparison*: with substructure analysis vs. with PGS



$H_T > 1$ TeV, $\not{E}_T > 300$ GeV
3^+ high-p_T jets, no leptons
1 candidate Higgs



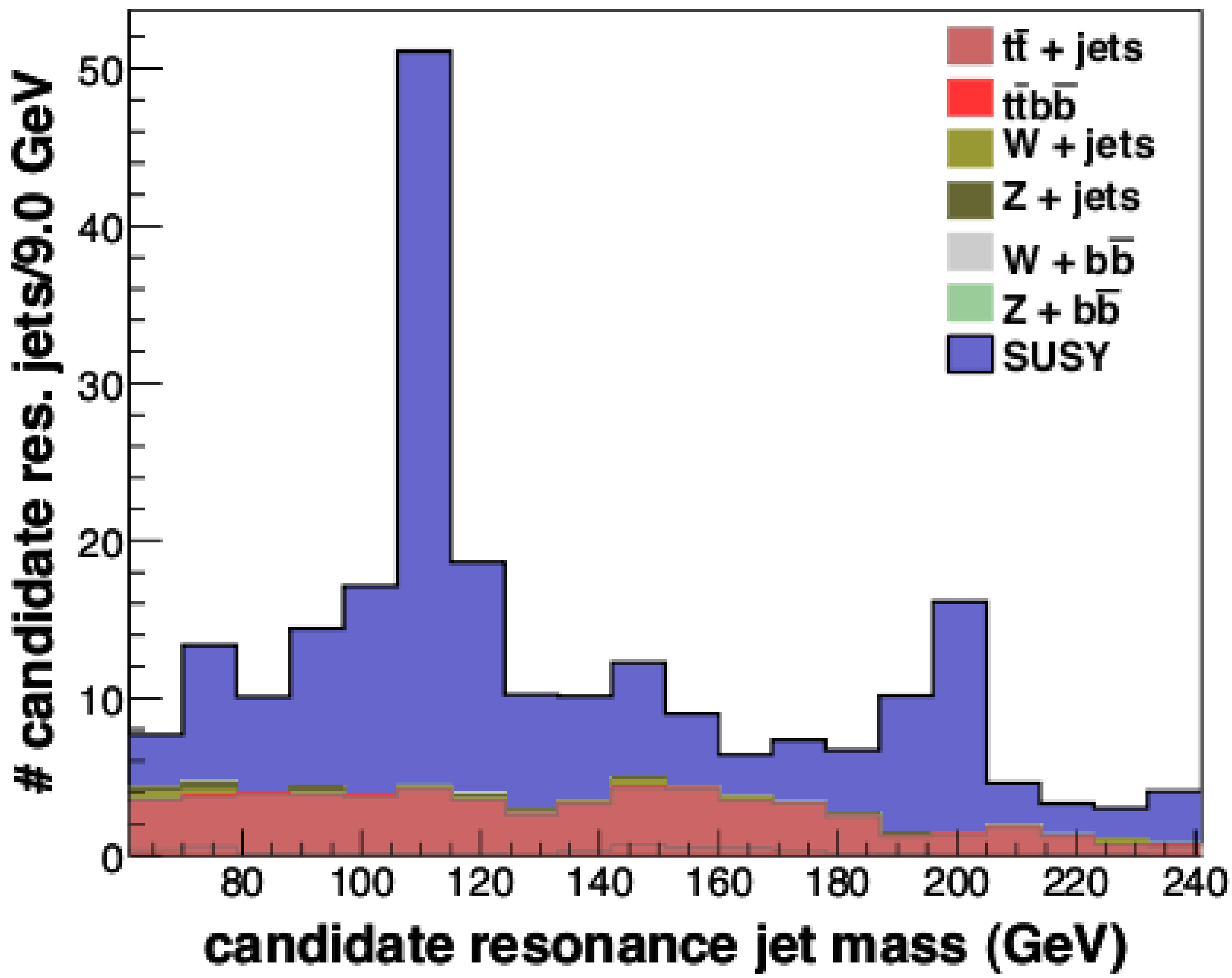
$H_T > 1$ TeV, $\not{E}_T > 300$ GeV
4^+ high $- p_T$ jets, no leptons
2^+ b-tags

(Stolen from A. Martin slides)

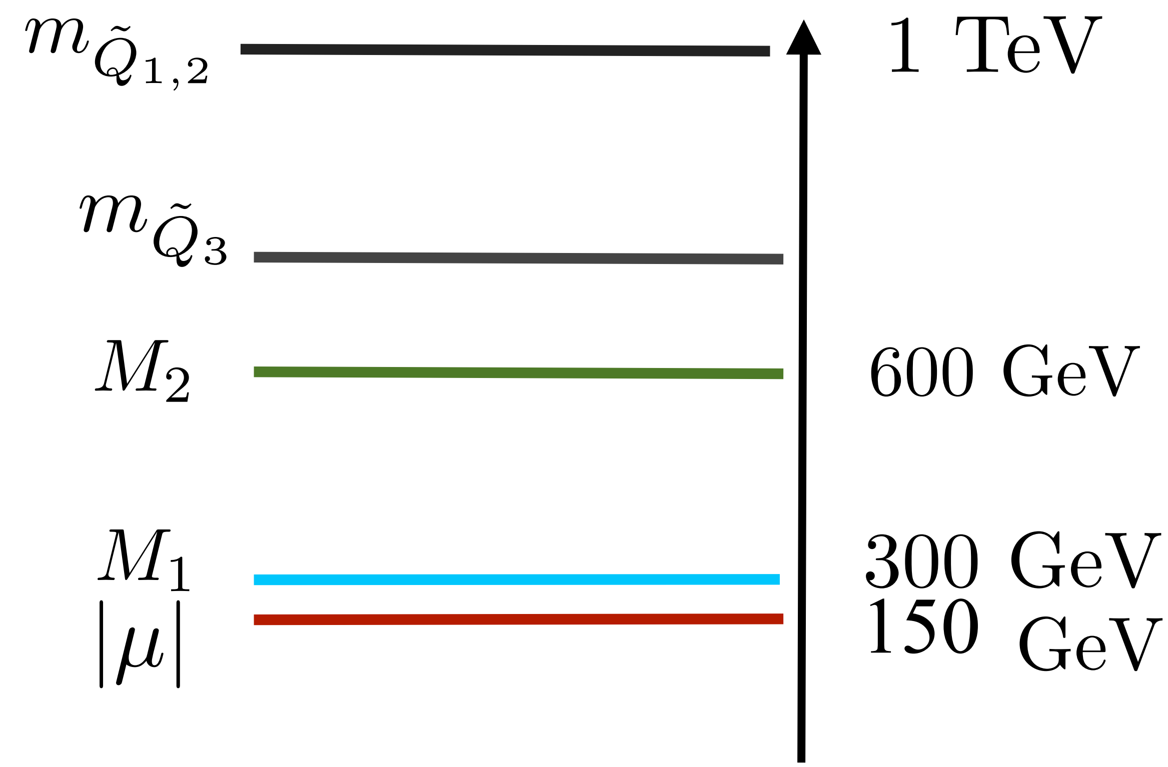
*not totally fair

Example 2: MSSM with m_A = 200 GeV

10 fb^{-1} @ 14 TeV

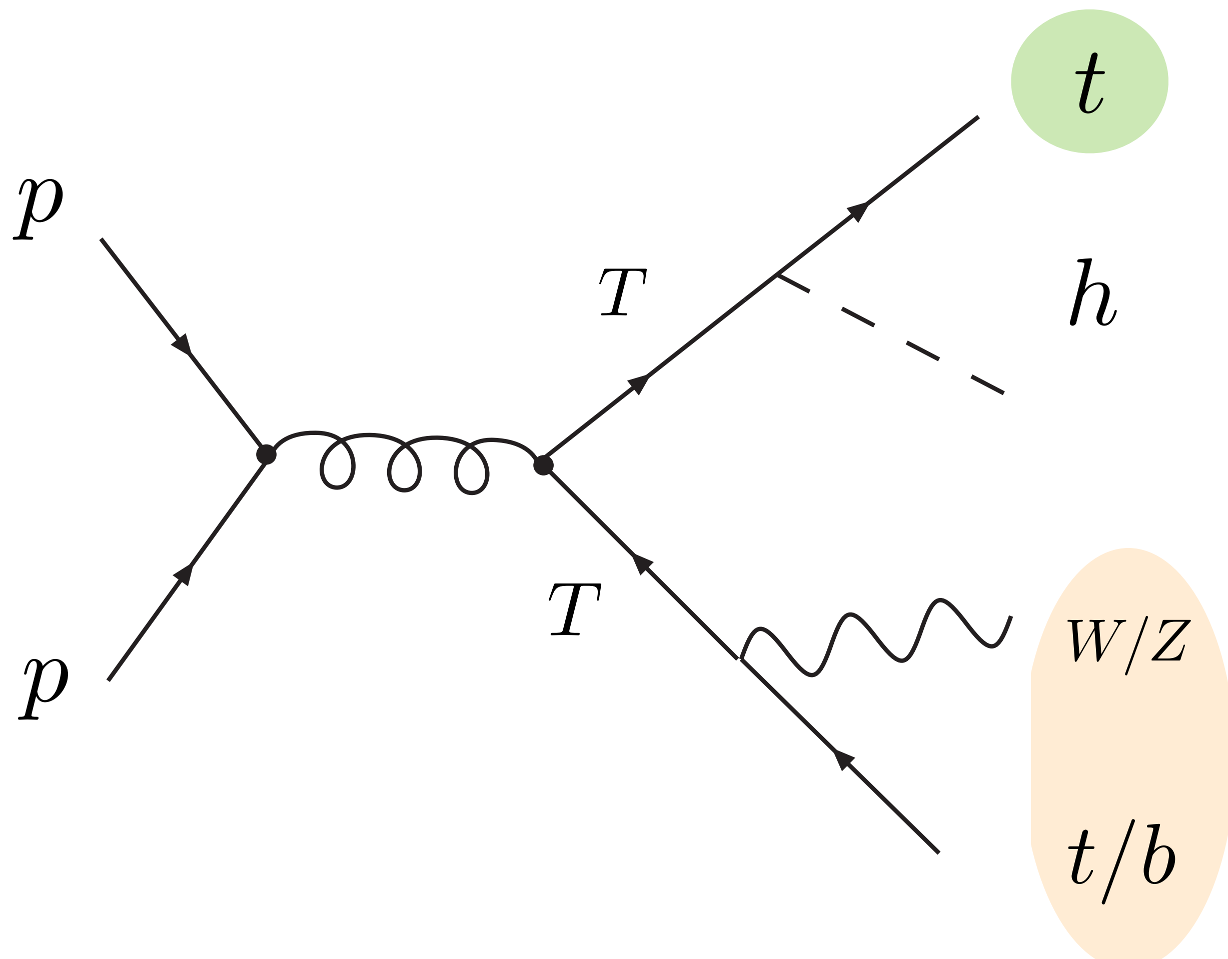


GK, Martin, Roy, Spannowsky; 1006.1656



Could discover heavier A,H states!

Example 3: Higgs from Top-Partners



always one top quark

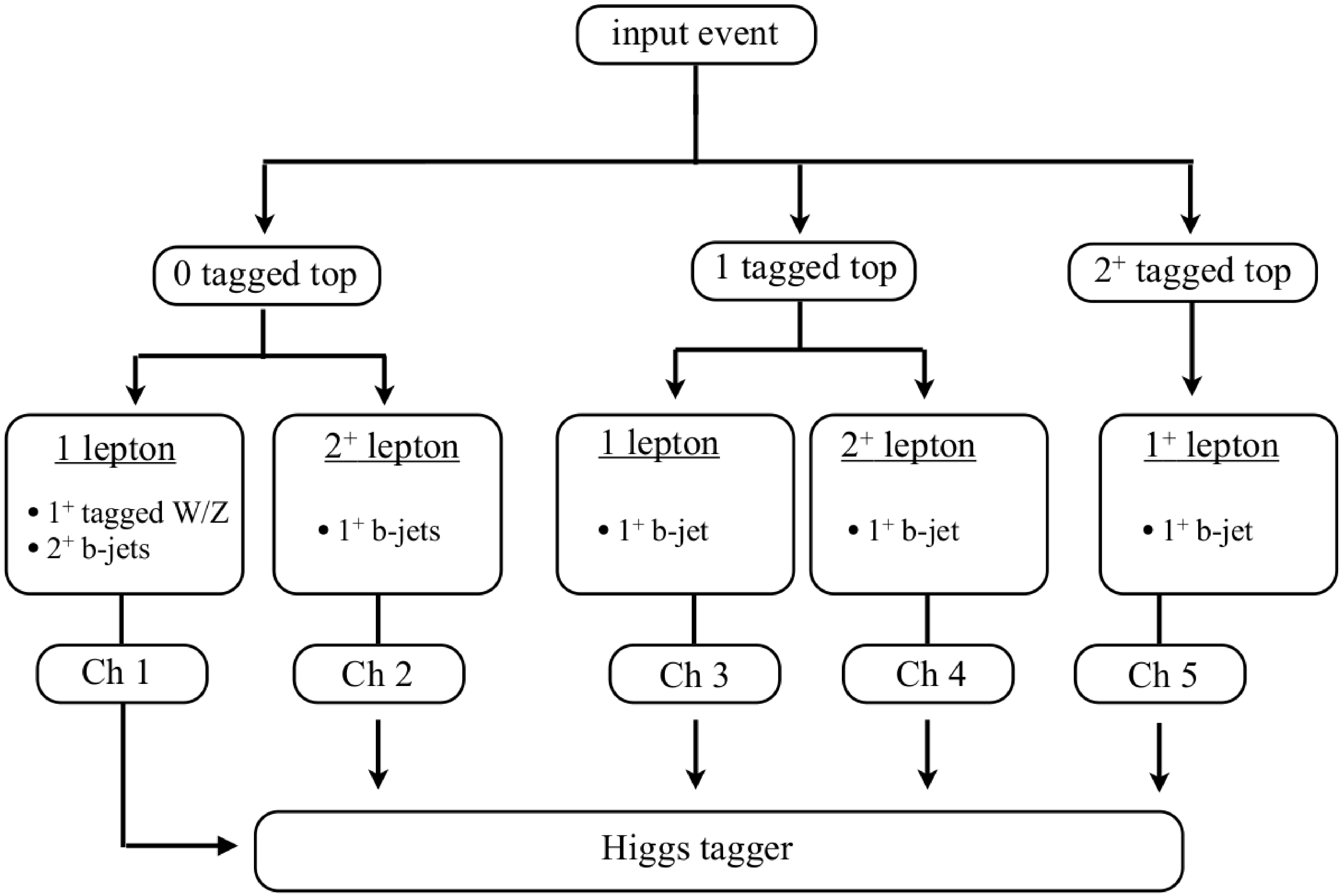
short cascade:
Higgs $p_T \sim M_T/2$
(vs. $\sim M_T/4$ for MSSM)

+ additional gauge boson/top

4^+ bs, many jets!

Unlike SUSY, require multiple "tags" involving the varied final states, including boosted top and boosted W tagging.

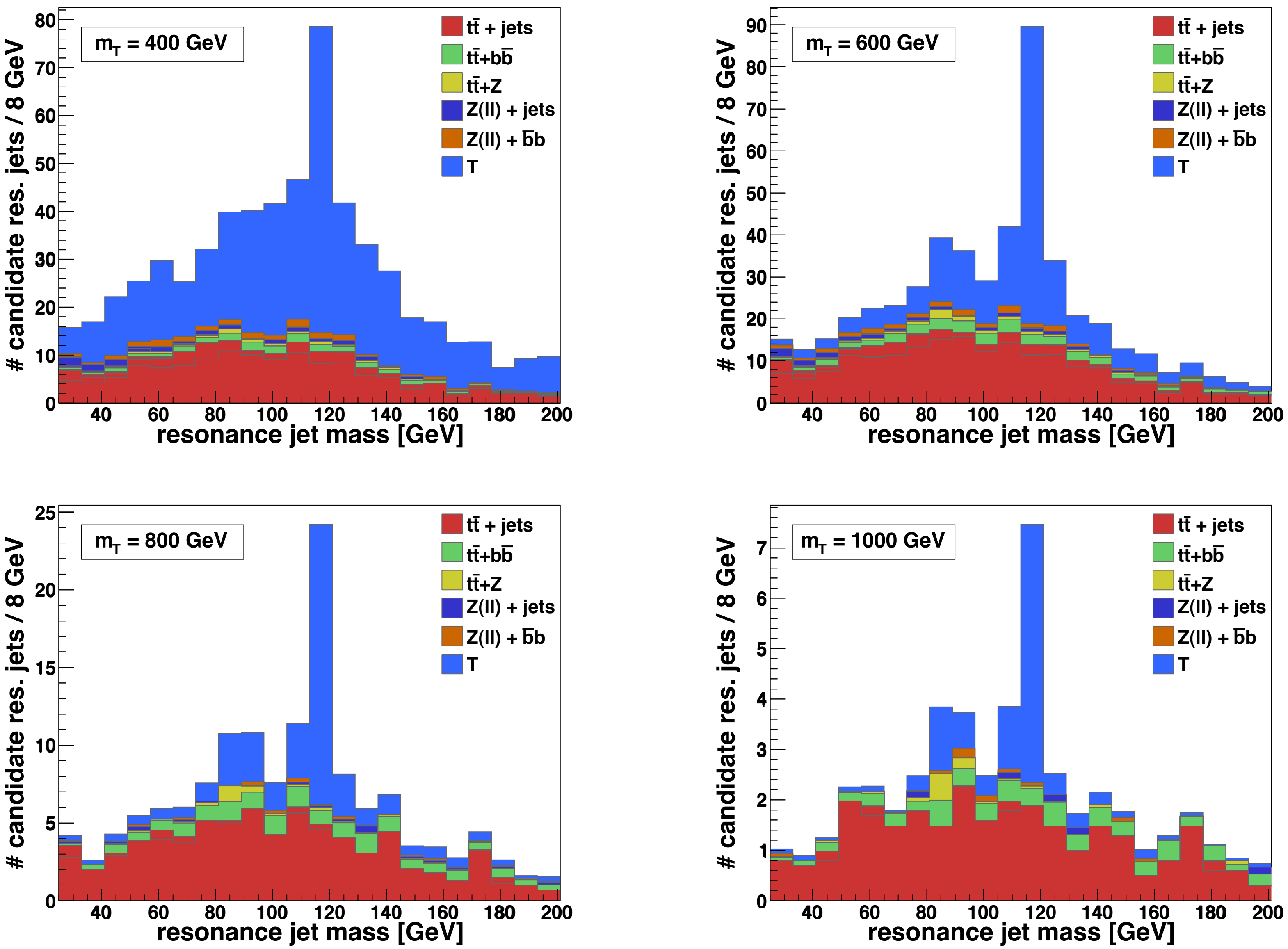
Example 3: Higgs from Top-Partners

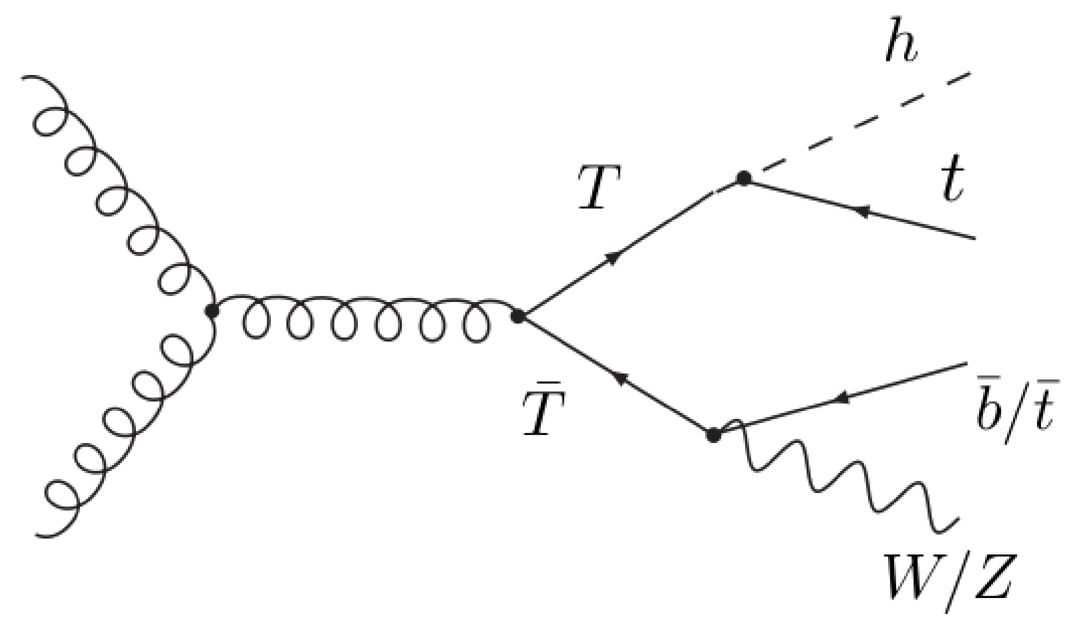


Different pathways better for different t′ masses.

Top partner production & decay:

10 fb^{-1} @ 14 TeV





GK, Martin, Roy; 1012.2866

Summary

- Jet substructure techniques are revolutionizing search for complicated hadronic final states

- MSSM h ideal candidate; large rate from squark production; large boost from cascade decay. Could discover h faster than SM!

Rethink m_A -tan(b) plane!!

- Top-partners produced with large rate; large boost; large decay fraction into Higgs; can also help discover and measure top-partner properties.

- Remarkable opportunities -- requires validation

"We"

Adam Martin — Fermilab postdoc

Tuhin Roy — UW postdoc

Michael Spannowsky — UO->SLAC postdoc

"Discovering the Higgs Boson in New Physics Events using Jet Substructure"
0912.4731 [PRD 2010]

"Discovering Higgs Bosons of the MSSM using Jet Substructure"
1006.1656 [PRD 2010]

"Higgs Discovery through Top-Partners using Jet Substructure"
1012.2866